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GRACE Bioremediation Technologies Daramend™ Bioremediation Technology

Innovative Technology Evaluation Report

NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
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Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

This report summarizes the results and activities of the demonstration of GRACE Bioremediation Technologies DARAMEND™ Bioremediation Technology for the treatment of soils contaminated with polynuclear aromatic hydrocarbons (PAHs) and chlorinated phenols, including pentachlorophenol (PCP). The primary market for the DARAMEND™ Bioremediation Technology consists of industrial wood preserving facilities that have used chlorinated phenols and creosote derived PAHs as wood preservatives. This technology is patent pending and was developed by GRACE Bioremediation Technologies in Mississauga, Ontario, Canada. The demonstration was conducted at the Domtar Wood Preserving Facility in Trenton, Ontario, under the USEPA's Superfund Innovative Technology Evaluation (SITE) Program.

This demonstration was conducted for the Risk Reduction Engineering Laboratory (now the National Risk Management Research Laboratory) in October 1993 to September 1994, and the final report was completed as of November 1995.

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Acronyms, Abbreviations and Symbols

mg	Microgram
µg/kg	Micrograms per kilogram
µg/l	Micrograms per liter
A0	Administrative Order
AQCR	Air Quality Control Regions
AQMD	Air Quality Management District
ARAR	Applicable or relevant and appropriate requirements
ATTIC	Alternative Treatment Technology Information Center
BTEX	Benzene, toluene, ethylbenzene, and xylene
CAA	Clean Air Act
CCME	Canadian Council of Ministers for the Environment
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERI	Center for Environmental Research Information
CFR	Code of Federal Regulations
CFU	Colony Forming Units
CI	Confidence intervals
cm	Centimeters
CO	Carbon Monoxide
CO^2	Carbon Dioxide
CP	Chlorinated Phenol
CWA	Clean Water Act
DQO	Data Quality Objective
EIT	Environmental Improvement Technologies
EPA	U.S. Environmental Protection Agency
ESD	Explanation of Significant Difference
FS	Feasibility Study
hp	Horsepower
ITER	Innovative Technology Evaluation Report
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-hour
MCL	Maximum contaminant levels
CLG	Maximum contaminant level goals
MDL	Minimum Detection Limit
mg/kg	Milligrams per kilogram
mg/l	Milligrams per liter
NAAQS	National Ambient Air Quality Standards
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
ND	Non-Detect
NPDES	National Pollutant Discharge Elimination System
NRMRL	National Risk Management Research Laboratory
NTIS	National Technical Information Service
ORD	EPA Office of Research and Development
OSHA	Occupational Safety and Health Act
OSWER	Office of Solid Waste and Emergency Response
PAH	Polynuclear Aromatic Hydrocarbon

Acronyms, Abbreviations and Symbols (Continued)

PCA	Plate Count Agar
PCB	Polychlorinated biphenyl
PCE	Tetrachloroethane
PCP	Pentachlorophenol
POTW	Publicly Owned Treatment Works
PPE	Personal protective equipment
PSD	Particle size distribution
RCRA	Resource Conservation and Recovery Act
S.U.	Standard Units
SAIC	Science Applications International Corporation
SARA	Super-fund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
SITE	Super-fund Innovative Technology Evaluation
SWDA	Solid Waste Disposal Act
TC	Total Carbon
TCP	Total Chlorinated Phenols
TER	Technology Evaluation Report
THC	Total Hydrocarbon Compounds
TIC	Total Inorganic Carbon
TKN	Total Kjeldahl Nitrogen
TPAH	Total Polycyclic Aromatic Hydrocarbons
TPH	Total Petroleum Hydrocarbons
TRPH	Total Recoverable Petroleum Hydrocarbons
TSCA	Toxic Substances Control Act
TSD	Treatment, Storage, and Disposal
UST	Underground Storage Tank
VISITT	Vendor Information System for Innovative Treatment Technologies
VOC	Volatile Organic Compound
WHC	Water Holding Capacity
yd^3	Cubic yards

Acknowledgments

This report was developed under the direction of Teri Richardson, the EPATechnical Project Manager for this SITE demonstration at NRMRL in Cincinnati, Ohio.

This report was prepared by the Environmental Technology Division of Science Applications International Corporation (SAIC), Hackensack, NJ under the direction of Michael M. Bolen, the SAIC Work Assignment Manager, for the EPA under Contract No. 68-CO-0048. This report was written in large part by Mr. Bolen, John King, Omer Kitaplioglu, and Dr. Robert Hoke. Statistical analyses and the experimental design were developed by Kirk Cameron and Dan Patel. Project Quality Assurance was provided by Rita Schmon-Stasik and Joseph Evans. Field management responsibilities were performed by Steve Stavrou, with the exception of the baseline event, which was overseen by William Dorsch. Technical support was provided by Dr. Scott Beckman, Dr. Herbert Skovroneck, Joseph Zollo, Andrew Matuson, Antonia Laros, Brandon Phillips, Paul Feinberg, Kate Mikulka, and Nicole Hart.

The cooperation and participation of Alan Seech, Paul Bucens, Dean Fisher, Brian O'Neill, and supporting staff of GRACE Bioremediation Technologies throughout the course of the project and in review of this report are gratefully acknowledged.

Special thanks are offered to the employees at the Domtar Wood Preserving Facility for their hospitality and assistance throughout this SITE demonstration.

Executive Summary

This report summarizes the results and activities of the demonstration of GRACE Bioremediation Technologies' DARAMEND™ Bioremediation Technology for the treatment of soils contaminated with polynuclear aromatic hydrocarbons (PAHs) and Chlorinated Phenols (CPs), including pentachlorophenol (PCP). The primary market for the DARAMEND™ technology consists of industrial wood preserving facilities that have used CPs and creosote derived PAHs as wood preservatives. This technology is patent pending and was developed by GRACE Bioremediation Technologies in Mississauga, Ontario, Canada. The demonstration was conducted at the Domtar Wood Preserving Facility in Trenton, Ontario, under the U.S. Environmental Protection Agency's (USEPA's) Superfund Innovative Technology Evaluation (SITE) Program.

The DARAMEND™ Bioremediation Technology is a bioremediation process that treats soils contaminated with PAHs and CPs by adding and distributing solid-phase organic amendments according to a strict application, monitoring, and maintenance program. According to the developer, the DARAMEND™ Bioremediation Technology reduces the acute toxicity of the soils aqueous phase by transiently binding soil contaminants and allowing bioremediation to proceed in highly toxic soils. Furthermore, the developer claims the DARAMEND™ Bioremediation Technology is an effective bioremediation alternative for the treatment of soils containing high levels of CPs and PAHs, which are typically considered too toxic for bioremediation. The traditional treatments for these soils include soil washing, incineration, or landfilling. There are approximately 400 industrial wood treatment facilities in the United States and an additional 200 sites in Canada that exhibit soils contaminated with CPs and creosote. The Appendix contains additional information presented by the developer, GRACE Bioremediation Technologies.

Under the SITE Program, the technology was evaluated to determine its effectiveness in reducing PAHs and CPs in excavated soil at the Domtar site, after a proposed 240 days of treatment (actual 254 days). The technology was evaluated against the nine criteria for decision-making in the Superfund Feasibility Study Process. Table ES-l summarizes the specific federal environmental regulations pertinent to the operation of the DARAMEND™ Bioremediation Technology, including the transport, treatment, storage, and disposal of wastes and treatment residuals.

The DARAMEND™ Bioremediation Technology is applicable to the in situ and ex situ remediation of soils contaminated with PAHs and CPs. According to the developer, the technology has been proven on soils with PAH concentrations up to 18,500 mg/kg, total petroleum hydrocarbon concentrations up to 8,700 mg/kg, and PCP concentrations up to 660 mg/kg. However, soils with extremely high concentrations of target compounds (i.e., 1800 mg/kg of PCP) have proven resistant to the DARAMEND™ Bioremediation Technology. The technology is a simple soil remediation system, both in design and implementation. The process involves a certain amount of materials handling: the ex situ application more so than the ***in situ*** application. The ex situ application is similar to landfarming technologies in that a large amount of space is required to treat the soils. In an ex ***situ*** application, the process is designed to generate no leachate. The process does not require any major utilities to operate. Inhibitors to the technology are inordinate amounts of debris in the soil, acidic soils (pH <2), and elevated heavy metal concentrations in the soil (not yet determined by the developer). According to the developer, the DARAMEND™ Bioremediation Technology appears to be limited to soils contaminated with nonhalogenated and slightly halogenated organic compounds and is not suited for soils contaminated with PCBs and other highly halogenated organics.

A full-scale clean up of this demonstration site using this technology was estimated to cost between $619,000 for an ***in situ*** plot case with an attendant unit cost of $92/m^3$ ($70/yd³), and $959,000 for an ex ***situ*** plot case with an attendant unit cost of $140/m³ ($1 08/yd³). These costs were calculated based on the following assumptions: an equal soil volume (6,800 m³); a treatment depth of 0.6 m; a treatment period of 11 months to meet regulatory standards; one treatment cycle for the ***in situ*** plot; and five treatment cycles for the ex ***situ*** plot, since the ex ***situ*** plot can only accommodate 2,300 m² of soil per cycle. For both cases above, residuals and waste shipping and handling charges were the predominant cost. Without residuals disposal, the unit costs decrease to $46/m³ ($35/yd³) for the ***in situ*** plot, representing a 50% reduction, and $96/m³ ($73/yd³) for the ex ***situ*** plot, representing a 31% reduction. No costs

Table ES-l. Feasibility Study Criteria Evaluation for the DARAMEND™ Bioremediation Technology

Overall Protection of Human Health and the Environment	Compliance with Federal ARARS	Long-Term Effectiveness and Permanence	Reduction of Toxicity, Mobility, or Volume Through Treatment	Short-Term Effectiveness	Implementability	Cost	Community Acceptance	State Acceptance
Provides both short- and long-term protection by reducing or eliminating organic (PAHs and TCPs) contaminants in soil.	Requires compliance with RCRA treatment, storage, and land disposal regulations (of a hazardous waste).	Provides for irreversible treatment of PAHs and TCPs.	Significantly reduces toxicity, mobility, and volume of soil contaminants through treatment.	The DARAMEND™ Bioremediation Technology requires a period of approximately 240 days for the degradation of contaminants to reach regulatory standards. Length of time is based on contaminant type, concentration levels, and the characteristics of the media.	Involves few administrative difficulties.	A first estimate cost is $50 to $80 USD/ton. The cost is affected by project parameters such as contaminant type and initial concentration; soil volume requiring remediation; climate; remediation time frame; and project scope of work.	Minimal short-term risks to the community make this technology appealing to the public.	State ARARs may be more stringent than federal regulations.
Removes existing contamination source, thereby preventing continual contamination to other environmental media.	Excavation, construction, and operation of onsite treatment unit may require compliance with location-specific ARARs.	Prevents further ground water contamination and pollutant migration.	Eliminates contamination source, thus reducing the mobility of contaminants to other environmental media.		System is easy to install and operate. Uses conventional excavation and tilling equipment.		Technology is generally accepted by the public because it provides a permanent solution.	State acceptance of the technology varies depending upon ARARs.
Requires measures to protect workers and community during excavation, handling, and treatment.	Process does not generate significant air emissions or wastewater during implementation of treatment.		Volume of soil after treatment is slightly increased due to the addition of treatment amendments.		May require a greenhouse type enclosure to ensure proper soil temperature and humidity.		Noise generated during system installation could be troublesome, but once the process is operational it does not generate much appreciable noise.	

were assigned for effluent treatment and disposal since no leachate was generated for the ex situ case. This was also assumed for the *in situ* case at the demonstration site, although the developer indicated that pilot-scale testing at other sites would be required. For both cases, labor and site preparation were among the top four cost categories, after residual and waste shipping and handling costs, costs attributed to analytical services, capital equipment, demobilization, permitting, and regulatory requirements are about the same for both cases. The evaluation of the ex situ application of the technology was the primary focus of this SITE demonstration.

The EPA SITE demonstration area consisted of two plots, a Treatment Plot and a No-Treatment Plot, containing excavated contaminated soil from the same source on-site (former processing area). The plots were constructed identically, with the exception that the No-Treatment Plot was only 2 m x 6 m, and the Treatment Plot was a 6 m x 36 m area. The No-Treatment Plot was left idle over the course of the demonstration and was isolated from the treatment process. The Treatment Plot consisted of a 12-inch thick layer of excavated soil targeted for the DARAMEND™ Bioremediation Technology and evaluation by the SITE Program. Once the organic amendments were mixed into the Treatment Plot soil, monitoring and maintenance of the Treatment Plot occurred over a period of 11 months. A total of 254 treatment days occurred, excluding days during which the soil temperature fell below 15°C. GRACE Bioremediation Technologies, the developer, monitored the plot at least biweekly, by measuring the soil temperature, soil water holding capacity, soil moisture, and air temperatures, and by conducting Microtox™ soil toxicity assays. Maintenance of the Treatment Plot consisted of biweekly tillage and irrigation of the soil.

The demonstration of the DARAMEND™ Bioremediation Technology was conducted from October 1993 to September 1994 at the Domtar site. The Domtar site is located 90 miles east of Toronto, Ontario, along the northern coast of Lake Ontario. The site was a wood-preserving facility for several decades; otherwise, very little is known about the history of the site. The facility is currently used to store treated lumber, railroad ties, and telephone poles. Past wood preserving operations used PCP (a chlorinated phenol compound), petroleum hydrocarbons, and creosote-derived PAHs in their processes. As a result the surrounding soil was contaminated by accidental spills and by drippings during the drying process. Recently, some of this contaminated soil was excavated and stockpiled for treatment by GRACE Bioremediation Technologies. This excavated soil was utilized during the SITE demonstration.

The primary objective of the SITE demonstration was to evaluate the technology's ability to reduce total PAHs and total CPs (TCPs) in the Treatment Plot, which was expected to be on the order of 95%, over a period of 240 days (eight months) of treatment. To accomplish this objective the Treatment Plot was sampled at the start (day 0) and at the end of the demonstration (day 254), as well as during two intermediate periods. Soil samples were analyzed for semi-volatile organic compounds (SVOCs, by SW846 EPA Method 3540/8270), which included PCP and selected PAHs.

Process performance was evaluated by comparing the concentrations of the following analytes before and after treatment:

Total PAHs

- Naphthalene
- Acenaphthalene
- Acenaphthene
- Fluorene
- Phenanthrene
- Anthracene
- Benzo(g,h,i)Perylene
- Fluoranthene
- Pyrene
- Chrysene
- Benzo(a)pyrene
- Benzo(b)fluoranthene
- Benzo(k)fluoranthene
- Benzo(a)anthracene
- Indeno(l,2,3-c,d)pyrene
- Dibenzo (a,h)anthracene
- Benzo (g,h,i) perylene

Total Chlorophenols

- 2-chlorophenol
- 2,4-dichlorophenol
- 2,4,5-trichlorophenol
- 2,4,6-trichlorophenol
- Pentachlorophenol

The total list of chlorophenols presented by the developer has been abbreviated to the above list to include those analytes routinely analyzed under SW846 354018270.

As the process is temperature-dependent, the treatment period only incorporates days when the average daily soil temperature within the plot was above 15°C. Originally, the demonstration was scheduled to run until the beginning of June 1994, but was extended to the end of September due to the number of days the soil temperature fell below 15°C during the winter months.

As part of the secondary objectives a variety of parameters were evaluated as listed below:

- Determine the magnitude of reduction in the sums of the concentrations of select PAHs and CPs in the No-Treatment Plot soils.

- Determine the magnitude of reduction for specific and chlorinated phenolic compounds within each of the SITE demonstration plots.

- Determine the toxicity of the soil to earthworms and seed germination in each of the SITE demonstration plots before and after treatment.

- Monitor the fate of total recoverable petroleum hydrocarbons (TRPH) in each of the SITE demonstration plots.

- Monitor general soil conditions (i.e., nutrients, toxins) that might inhibit or promote process effectiveness, such as total carbon (TC), total inorganic carbon (TIC), nitrate-nitrite, phosphate, total kjeldahl nitrogen (TKN), pH, particle size distribution (PSD), chlorides and total metals within each of the SITE demonstration plots.

- Monitor for the presence of leachate within the SITE demonstration Test Plot.

- Monitor each of the SITE demonstration plots for active microbial populations, specifically focusing on total heterotrophs and PCP degraders, as a way to qualitatively assess the magnitude of biodegradation over the course of the eight-month test.

- Monitor the upper sand layer in contact with the treated soil to qualitatively assess any tendency for downward migration of contaminants.

These primary and secondary project objectives were achieved through a carefully planned and executed sampling and analysis plan. For this demonstration SVOCs were considered critical during "Baseline" and "Post-Treatment" sampling (Event #0 and Event #3) of the SITE demonstration Treatment Plot. This parameter was considered noncritical during sampling of the No-Treatment Plot and during the two intermediate rounds of Treatment Plot sampling (Event #l and Event #2). The period of performance evaluation was estimated by the developer to be approximately 240 days (actual 254 days) starting on October 14, 1993. A week in September marked the final Event #3 (254 days) or "Post Treatment Sampling" of the plots. The two intermediate rounds (Event #l and Event #2) occurred on the 88th day and on the 144th day of treatment in April 1994 and June 1994. No sampling was conducted during the months of November, December, January, February, and March since little biodegradation was expected to occur at low winter temperatures.

An additional objective of this demonstration was to develop data on operating costs for the DARAMEND™ Bioremediation Technology so that the applicability and cost effectiveness of this process at other sites can be evaluated. Capital costs were obtained from the developer. Operating and maintenance costs were either estimated or obtained from the developer. Estimates for labor requirements were developed using observations made and data gathered during the demonstration. The companion document to this report is the Technology Evaluation Report (TER), which contains such information as quality assurance/quality control protocols, raw and summarized data, and project chronology.

Conclusions Based on Primary Objectives

The DARAMEND™ Bioremediation Technology achieved an overall 94% removal of PAHs (with a 90% confidence interval (Cl) of 93.4% to 95.2%) and an overall 88% reduction of TCPs (with a 90% confidence interval of 82.9% to 90.5%) after 254 days of treatment of the Treatment Plot ex situ soils. Total PAHs were reduced from an average of 1710 mg/kg to 98 mg/kg and TCPs were reduced from an average of 352 mg/kg to 43 mg/kg. Statistical comparison with 10% level of significance indicate that reductions of PAHs and chlorophenols realized in the Treatment Plot were significantly higher that those realized in the No-Treatment Plot (presented later in this section).

Conclusions Based on Secondary Objectives

The results of the demonstration suggest the following conclusions regarding the technology's performance at the Domtar site. These conclusions were based on secondary objectives:

No-Treatment Plot Total PAH and TCP Reduction Rates

- Results from the No-Treatment Plot indicate total PAHs were reduced by 41% (with a 90% Cl of 34.6% to 48.7%) and CPs were reduced 0%. Total PAHs were reduced from an average of 1312 mg/kg to 776 mg/kg and TCPs remained at an approximate average of 217 mglkg.

Treatment Plot - Specific PA H Compounds and Chlorinated Phenols

- The reduction of individual PAHs and CPs in the Treatment Plot ranged from approximately 98% to 41%. Statistical analysis indicated that the reductions observed were significant with a 90% confidence level. The 3-ring and 4-ring PAH compounds were reduced more significantly than the 5-ring and 6-ring PAH compounds. The approximate average reduction rate of 3-ring and 4-ring PAH compounds was 97%; 5-ring and 6-ring PAH compounds averaged approximately 77% and 40% removal, respectively.

No-Treatment Plot - Specific PAH Compounds and Chlorinated Phenols

- The reduction of individual PAHs and CPs in the No-Treatment Plot ranged from approximately 76% to 0%. The 3-ring and 4-ring PAH compounds were reduced more significantly than the 5-ring and 6-ring PAH compounds. The approximate average reduction rates of 3-ring and 4-ring PAH compounds were 64% and 34%, respectively. In comparison, the 5-ring and 6-ring PAH compounds averaged approximately 16% and 20% removal, respectively.

Toxicity

- Toxicity analysis results indicate that the treatment process appeared to reduce the toxicity of the Treatment Plot soil to both the earthworms and plant seeds. At the end of the treatment process, the Treatment Plot soil sample was considered nontoxic. The earthworms in the Treatment Plot soil exhibited a 100% mean mortality rate during the baseline. After 254 days of treatment by the DARAMEND™ Bioremediation

Technology, earthworms exhibited a 0% mean mortality rate. Plant seeds in the Treatment Plot soil exhibited a 100 to 52% mean inhibition of germination rate (lettuce and radish, respectively) during the baseline. After 254 days of treatment, lettuce and radish seeds exhibited a 33% and 0% mean inhibition of germination rate, respectively. The No-Treatment Plot exhibited only a slight reduction in toxicity and the soil remained toxic. Only radish seed germination changed from 82% mean inhibition to 28% mean inhibition in the No-Treatment Plot (others exhibited practically no change). This slight reduction in toxicity of the No-Treatment Plot soils is consistent with the slight reduction in PAHs observed.

Total Recoverable Petroleum Hydrocarbons

- The results of the TRPH data for each plot indicated significant reductions occurred in the Treatment Plot (87%) and no reduction in the No-Treatment Plot (0%).

Soil Chemistry

- A significant reduction of PAHs and CPs in the Treatment Plot soil was exhibited despite the concentrations of metals and conventional soil chemistry present. The soil was primarily free of any inhibitors that may have impeded the biodegradation of the PAHs and CPs. The metals concentrations ranged from 6690 mg/kg of iron to 1 mg/kg of cadmium. Levels of pH ranged from 8.16 to 9.38 in the Treatment Plot. In addition, other soil chemistry analyses (e.g., nitrate-nitrite, total organic carbon, etc.) gave no evidence that nutrient levels in the soil were increased as a result of the treatment process. The No-Treatment Plot exhibited relatively the same soil chemistry as the Treatment Plot over the duration of the demonstration. Only TIC was elevated in the Treatment Plot (26,300 mg/kg to 216,000 mg/kg) in comparison to the No-Treatment Plot (13,800 mg/kg to 96,200 mglkg).

- Analysis of chlorinated dioxins and furans in the Treatment Plot at the beginning and end of the project indicated the presence of low concentration of various penta-, hexa-, and hepta- congeners in both soils. The major constituents were the fully chlorinated congeners. The toxic congener 2,3,7,8-TCDD was absent. Decreases, if any, in totals for tetra-, hexa-, hepta- octa-congeners would lead one to suspect that a decrease has occurred over the course of the demonstration.

Leachate Monitoring

- No leachate was generated as a result of the treatment process.

Microbial Biomass Populations

- The magnitude of biodegradation was enhanced by the treatment process and inhibited by the PCP, as measured by colony forming units (CFU) of total heterotrophic microbial biomass. In addition, the microbial data suggests that high total PAH concentrations in the soil had an inhibiting effect on the microbial biomass of the demonstration soil, including organisms that may be capable of metabolizing PCP. A large degree of variability (i.e., standard deviation) was associated with these conclusions, and they may not be statistically significant. However, all observed trends were consistent and biologically plausible.

Pollutant Migration Monitoring

- Evaluation of the possible downward migration of contaminants was compromised prior to the demonstration and during the demonstration by the developer. No conclusions can be substantiated.

Operability and Overall Performance

- The operability and overall performance of the technology was very satisfactory. The treatment process was installed, monitored, and maintained by the developer as designed. Only one incident occurred: the underlying clean sand layer was accidentally mixed with the overlying demonstration soils during the demonstration (prior to the 88th day of treatment). Possible dilution calculations indicate that this incident had an insignificant effect (i.e., PCP approximately 2%) on the overall performance of the technology. Section 4.4.4 discusses this in more detail.

The findings of this SITE demonstration are supported by several complementary observations, all of which demonstrate that the contaminants were removed by the DARAMEND™ Bioremediation Technology. These include (1) a statistical analysis of the first and last sampling episodes that indicate significant decreases in total PAHs and PCP; (2) intermediate measurements that show steadily declining values for these contaminants; (3) a marked decrease in TRPH over the duration of the test; (4) decrease in toxicity as measured by earthworm and seedling bioassays; and (5) bacterial plate counts that illustrate enhanced activity in the Treatment Plot. Taken together these observations are more convincing than any single set of data considered separately.

Other technology requirements for the implementation of the DARAMEND™ Bioremediation Technology may include permits for the treatment, storage, construction, possible air emissions, etc. Personnel issues are a factor depending on the scale of the remediation. Otherwise, health and safety issues for personnel are generally the same as those that apply at all hazardous waste treatment facilities. Community issues may occur depending on the community's exposure to noise and airborne particulate generated during site preparation and pretreatment activities.

The following sections of this report contain the detailed information that supports the items summarized in this Executive Summary.

This section provides background information about the SITE- Program, discusses the purpose of this Innovative Technology Evaluation Report (ITER), and describes the

DARAMEND™ Bioremediation Technology. For additional information about the SITE Program, this technology, and the demonstration site, key contacts are listed at the end of Section 1.

Section 1
Introduction

1.1 Background

The GRACE Bioremediation Technologies SITE demonstration was conducted to evaluate the performance of the developer's DARAMEND™ Bioremediation Technology in remediating PAH and chlorinated phenol contamination in wood-treatment soils from the Domtar Wood Preserving Facility in Trenton, Ontario. According to the developer, the DARAMEND™ Bioremediation Technology is an effective bioremediation alternative to soil washing, incineration, or landfilling for soils containing high levels of CPs and PAHs, which are typically considered too toxic for bioremediation.

The primary markets for the DARAMEND™ Bioremediation Technology are industrial wood treatment facilities that have used CPs and creosote-derived PAHs as wood preservatives. There are approximately 400 such sites in the United States and an additional 200 in Canada. The DARAMEND™ Bioremediation Technology has been applied to five other PAH- and PCP-contaminated sites in Canada. According to the developer, the success of the technology with wood preserving chemicals, such as PAHs, has allowed the contaminant range to be extended to phthalates in soils. In addition, the developer states that a new bioremediation technology based on the DARAMEND™ Bioremediation Technology is being developed that rapidly reduces the concentrations of organochlorine pesticides and organic explosives in soil.

Prior to the developers participation in the EPA SITE Program, the technology underwent successful bench and pilot scale testing by the developer on soils from the demonstration site. During the developer's pilot-scale program, the reduction of in situ chlorinated phenol concentrations to below the Canadian Council of Ministers for the Environment (CCME) guideline of 5 mg/kg, and the 99% reduction of PCP (is a chlorinated phenol) concentration from 680 to 6 mg/kg, were reported. Total PAH concentrations were also reduced from 1485 mg/kg to 35 mg/kg during this time. In 1993, to assess the reliability and cost effectiveness of the technology, GRACE Bioremediation Technologies conducted a full-scale demonstration at the Domtar facility to treat 3000 tons of soil *in situ* and 1500 tons ex situ. Based on the results of the site characterization in September 1993 and some further soil screening, targeted test soils at the Domtar site were found to be acceptable for the demonstration of the DARAMEND™ Bioremediation Technology. The EPA SITE demonstration of the ex situ DARAMEND™ Bioremediation Technology was conducted over the next 11 months, from October 1993 to September 1994, at the Domtar site.

The Domtar Wood Preserving Facility is located in Trenton, Ontario, Canada, approximately 90 miles east of Toronto, along the northern coast of Lake Ontario (see Figure l-l). Very little is known about the history of the site, other than its long history (several decades) as a wood preserving facility. The wood treatment process resulted in the deposition of creosote, and petroleum hydrocarbons in the soil. The facility currently operates as a large storage yard for treated lumber, railroad ties, and telephone poles; however, all wood preserving operations have ended. SITE demonstration activities were conducted at the northern end of the Domtar property and utilized the excavated soils from the former wood treatment area (see Figure 1-2).

1.2 Brief Description of Program and Reports

The SITE Program is a formal program established by EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA). The SITE Program promotes the development, demonstration, and use of new or innovative technologies to clean up Superfund sites across the country.

The SITE Program's primary purpose is to maximize the use of alternatives in cleaning hazardous waste sites by encouraging the development and demonstration of new, innovative treatment and monitoring technologies. It consists of four major elements discussed below:

- the Emerging Technology Program
- the Demonstration Program,

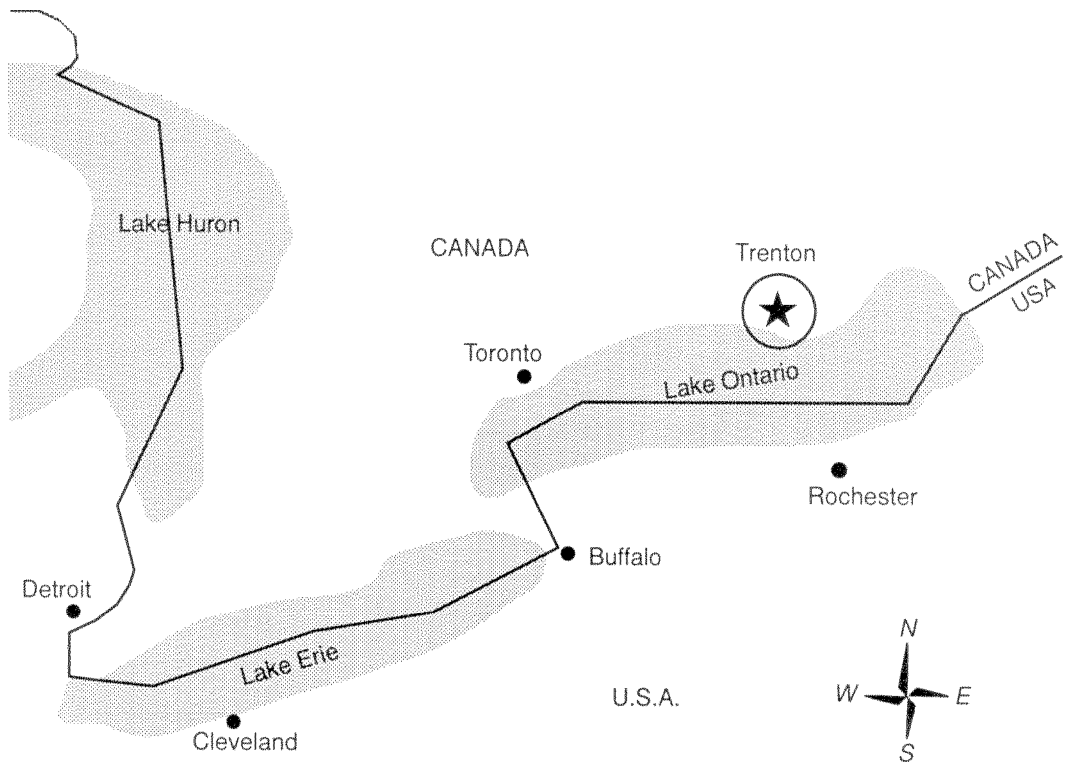

Figure I-I. Site Location Map Trenton, Ontario and Vicinity.

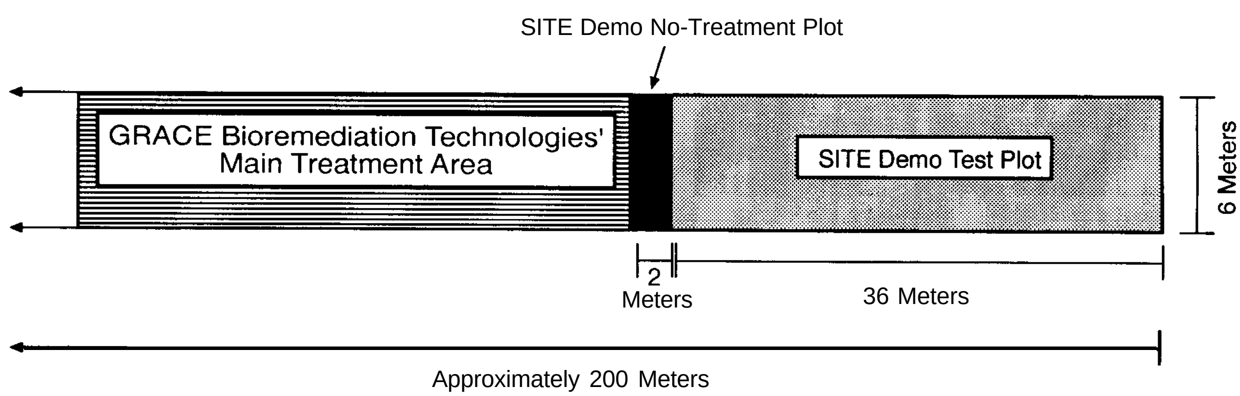

Figure 1-2. SITE Demonstration Plots in Relation to GRACE Bioremediation Technologies Plot.

- the Monitoring and Measuring Technologies Program, and
- the Technology Transfer Program.

The Emerging Technology Program focuses on conceptually proven bench-scale technologies that are in an early stage of development involving pilot or laboratory testing. Successful technologies are encouraged to advance to the Demonstration Program.

The Demonstration Program develops reliable performance and cost data on innovative technologies so that potential users may assess the technology's site-specific applicability. Technologies evaluated are either currently available or close to being available for remediation of Superfund sites. SITE demonstrations are conducted on hazardous waste sites under conditions that closely simulate full-scale remediation conditions, thus assuring the usefulness and reliability of information collected. Data collected are used to assess (1) the performance of the technology, (2) the potential need for pre- and post-treatment processing of wastes, (3) potential operating problems, and (4) the approximate costs. The demonstrations also allow for evaluation of long-term risks and operating and maintenance costs.

Existing technologies that improve field monitoring and site characterizations are identified in the Monitoring and Measurement Technologies Program. New technologies that provide faster, more cost-effective contamination and site assessment data are supported by this program. The Monitoring and Measurement Technologies Program also formulates the protocols and standard operating procedures for demonstrating methods and equipment.

The Technology Transfer Program disseminates technical information on innovative technologies in the Emerging Technology Program, Demonstration Program, and Monitoring and Measurement Technologies Programs through various activities. These activities increase the awareness and promote the use of innovative technologies for assessment and remediation at Superfund sites. The goal of technology transfer activities is to develop interactive communication among individuals requiring up-to-date technical information.

1.3 The SITE Demonstration Program

Technologies are selected for the SITE Demonstration Program through annual requests for proposals. ORD staff review the proposals to determine which technologies show the most promise for use at Superfund sites. Technologies chosen must be at the pilot- or full-scale stage, must be innovative, and must have some advantage over existing technologies. Mobile and *in situ* technologies are of particular interest.

Once EPA has accepted a proposal, cooperative agreements between EPA and the developer establish responsibilities for conducting the demonstrations and evaluating the technology. The developer is responsible for demonstrating the technology at the selected site and is expected to pay any costs for transport, operation, and removal of the equipment. EPA is responsible for project planning, sampling and analysis, quality assurance and quality control, report preparation, information distribution, and transport and disposal of treated waste materials.

The results of this evaluation of the DARAMEND™ Bioremediation Technology are published in two documents: the SITE Technology Capsule and the ITER. The SITE Technology Capsule provides relevant information on the technology, emphasizing key results of the SITE demonstration. TER is available as a supporting document to the ITER. Both the SITE Technology Capsule and the ITER are intended for use by remedial managers when making a detailed evaluation of the technology for a specific site and waste.

1.4 Purpose of the Innovative Technology Evaluation Report

This ITER provides information on the DARAMEND™ Bioremediation Technology and includes a comprehensive description of the demonstration and its results. The ITER is intended for use by EPA remedial project managers, EPA on-scene coordinators, contractors, and other decision makers in implementing specific remedial actions. The ITER is designed to aid decision makers in further evaluating specific technologies for consideration as applicable options in a particular cleanup operation. This report represents a critical step in the development and commercialization of a treatment technology.

To encourage the general use of demonstrated technologies, EPA provides information regarding the applicability of each technology to specific sites and wastes. The ITER includes information on cost and performance, particularly as evaluated during the demonstration. It also discusses advantages, disadvantages, and limitations of the technology.

Each SITE demonstration evaluates the performance of a technology in treating a specific waste. Waste characteristics at other sites may differ from those at the demonstration site. Therefore, successful field demonstration of a technology at one site does not necessarily ensure its applicability to other sites. Data from the field demonstration may require extrapolation to estimate the operating ranges in which the technology will perform satisfactorily. Only limited conclusions can be drawn from a single field demonstration.

1.5 Technology Description

GRACE Bioremediation Technologies' DARAMEND™ Bioremediation Technology treats soils contaminated with PAHs and CPs by adding and distributing solid-phase organic amendments according to a strict application/monitoring/maintenance program. The DARAMEND™

Bioremediation Technology is patent pending and consists of three components:

- Addition of solid-phase organic soil amendments of specific PSD and nutrient content,
- Distribution of the soil amendments through the target matrix and the homogenization and aeration of the target matrix using specialized tilling equipment, and
- A specialized soil moisture control system designed to maintain moisture content within a specified range, to facilitate rapid growth of an active microbial population and prevent the generation of leachate.

According to the developer, the organic amendments enable the soil matrix to supply biologically available water and nutrients to contaminant-degrading microorganisms, and transiently bind pollutants to reduce the acute toxicity of the soils aqueous phase, allowing the microorganisms to survive in soils containing very high concentrations of toxicants. After homogenization GRACE Bioremediation Technologies amendments are added to the soil in a volume of approximately 1 to 5% of the total volume of the soil. Addition of the amendments may increase the soil volume up to 15% depending on the amount of pore space present. Typically, amendments are added solely at the beginning of the treatment process, however, it is possible that approximately 10% of the original amount may need to be added midway or near the end of the treatment period, based on the soil sample analytical results. Once incorporated into the soil matrix, DARAMEND™ organic amendment particles are hydrated, begin releasing nutrients, and are rapidly colonized by microorganisms. The particles also have surface charges that electrostatically draw organic contaminants toward them. In this way the DARAMEND™ Bioremediation Technology creates many microsites where soil contaminants such as PCP are first drawn and then biodegraded. The enzymatic mechanism by which soil bacteria destroy PCP is well recognized and results in complete conversion of the contaminant to carbon dioxide, water, and chloride ions.

Tilling of the soil serves three functions: to reduce variations in soil physical and chemical properties; to increase the diffusion of oxygen to microsites; and to facilitate the uniform distribution of soil amendments. The soil matrix is homogenized by tilling with a power take-off driven rotary tiller. GRACE Bioremediation Technologies utilizes two tillers each of which is pulled by a 75 hp tractor. The tillers are 2.1 and 1.7 m wide and can reach an effective depth ‘of 60 cm.

In addition, the developer determines the water-holding capacity (WHC) of the targeted soils and employs a specialized soil moisture control system within a specific range to encourage the proliferation of large active microbial populations, yet limit the generation of leachate. The frequency of irrigation is determined by weekly monitoring of soil moisture conditions. The growth rate of microbial biomass is characterized via regular monitoring of soil temperature using a commercial version of a hand-held thermocouple.

Biweekly maintenance of the plots consists of the following tasks: plot tillage using a specialized tractor and tiller, soil monitoring for moisture and temperature, and plot irrigation. These are considered proprietary components of the developer's process.

The only form of pre-treatment required by the DARAMEND™ Bioremediation Technology is the mechanical screening of the soil (10 cm screen) in order to remove debris (rocks, wood, metal) that may interfere with distribution of the organic amendment. Screened soil is transported to the treatment area and spread uniformly in the constructed treatment plots to a maximum depth of 0.6 m. The constructed treatment plots consist of an area underlain with a high-density polyethylene liner (impermeable to the target compounds). This liner will be underlain with 10 cm of screened sand to prevent structural damage. Another 15-cm-thick sand layer and a 4-mm-thick fiberpad are spread on top of the liner to minimize the potential for direct contact between the liner material and tillage equipment. The demonstration ex situ treatment area covered an area of 2300 m^2 and allowed treatment of approximately 1500 tons of soil.

The treatment plots may also be contained within a temporary waterproof structure to produce a warmer environment in northern latitudes, and to aid in the retention of soil moisture. The waterproof structure consists of an aluminum frame covered by a shell of polyethylene sheeting and is left open at each end to allow for equipment access. *

1.6 Key Contacts

Additional information on the DARAMEND™ Bioremediation Treatment Process and the SITE Program can be obtained from the following sources:

The DARAMEND™ Technology

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The SITE Program

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Information on the SITE Program is available through the following on-line information clearinghouses:

- The Alternative Treatment Technology Information Center (ATTIC) System (operator: 513-569-7272; dial-in: 513-569-7610; telnet access: cinbbs.cin.epa.gov) is a comprehensive, automated information retrieval system that integrates data on hazardous waste treatment technologies into a centralized, searchable source. This database provides summarized information on innovative treatment technologies.

- The Vendor Information System for Innovative Treatment Technologies (VISITT) (Hotline: 800-245-4505; Fax: 513-891-6685) database contains information on 231 technologies offered by 141 developers.

- The OSWER CLU-In electronic bulletin board contains information on the status of SITE technology demonstrations (Operator: 301-589-8368; Access: 301-589-8366).

Technical reports may be obtained by contacting the Center for Environmental Research Information (CERI), 26 West Martin Luther King Drive, Cincinnati, OH 45268 at 513-569-7562.

Section 2
Technical Applications Analysis

An important aspect of the DARAMEND™ Bioremediation Technology is an understanding of the specific physical and chemical properties of the contaminated soil that could limit the effectiveness of bioremediation. The analysis is based on the SITE demonstration results, and conclusions are based exclusively on these data since only limited information is available on other applications of the technology. The EPA SITE Demonstration evaluated the *ex situ* version of the DARAMEND™ Bioremediation Technology, which involved the treatment of approximately 11 0m^3 of soil contaminated with PAHs and CPs, including PCP. Aseparate *in* situdemonstration of the DARAMEND™ Bioremediation Technology was also conducted during the same time frame but was not evaluated under the EPA SITE Program. The DARAMEND™ Bioremediation Technology has been successfully applied to soils with widely different physical and chemical properties.

2.1 Key Features

The DARAMEND™ Bioremediation Technology has been successfully applied to soils with widely different physical and chemical properties. DARAMEND™ Bioremediation Technology is generally an inexpensive remedial alternative and its remedial mechanism involves the complete destruction of contaminants, to CO_2 and H_2O. The technology is based upon the addition of specially formulated solid phase organic amendments of a specific PSD. In addition, these amendments are supplemented with controlled-release macronutrients and trace elements. According to the developer, the amendments increase the ability of the soil matrix to supply biologically available water and nutrients to stimulate indigenous populations of contaminant-degrading soil microorganisms. Furthermore, the developer claims that the amendments also transiently bind the contaminants to reduce the acute toxicity of the soil's: aqueous phase, thus allowing the microorganisms to survive in soil containing very high concentrations of contaminants. Hence, according to the developer, the DARAMEND™ Bioremediation Technology can effectively bioremediate soils traditionally considered too toxic for direct bioremediation.

2.2 Operability of the Technology

The DARAMEND™ Bioremediation Technology is relatively simple to operate. It consists of three integrated treatment components:

- Addition of the appropriate specially formulated solid-phase organic soil amendments to the target matrix
- Distribution of the soil amendments through the target matrix and the homogenization and aeration of the target matrix using specialized tilling equipment
- Soil moisture control using a specialized system to maintain moisture content within a specified range, to facilitate rapid growth of an active microbial population and control the generation of leachate.

For *in situ* applications of the technology, the soil is initially broken up with excavation equipment to a depth of 0.6 m, which is the limit for the specialized tilling equipment. The soil is broken up to reduce compaction and remove debris from the treatment zone. Following these initial soil preparation measures and the addition of amendments, the soil is tilled with a power takeoff driven rotary tiller. Tilling homogenizes the soil by effectively reducing the physical and chemical variations and evenly distributes soil amendments through the treatment zone.

For ex situ applications of the technology, contaminated soil is excavated and screened to 10 cm to remove debris (rocks, wood, metal) that might interfere with the incorporation of the organic amendments. Screened soil is then transferred to a contained treatment area consisting of a bermed concrete pad or a plastic lined treatment plot. These contained treatment areas are sized according to the volume of soil to be treated and the minimum space requirements for effective operation of the tilling equipment within the treatment plots. If a lined treatment plot is used, the HDPE plastic liner is underlain with 10 cm of screened sand to prevent structural damage to the liner. The liner is overlain by a 4mm thick fiberpad, and another sand layer, 15 cm thick, is spread on top of the fiberpad, to minimize the potential for direct contact between the liner and the tillage equipment. Once the upper bedding material is in place, the screened soil is deposited on top of the sand to a uniform depth of 0.5 m. Using a power take-off driven rotary tiller, the soil is homogenized to reduce the physical and chemical variations of the soil. As with the *in situ* application of the technology, the tilling equipment is also used to facilitate the uniform distribution of soil amendments. The contained treatment areas are typically covered by a waterproof, temporary structure to prevent excessive soil wetting due to rainfall and snow melt that would hinder biodegradation and lead to the generation of leachate.

An important aspect of the DARAMEND™ Bioremediation Technology is an understanding of the specific physical and chemical properties of the contaminated soil that could limit the effectiveness of bioremediation. This information is acquired during an initial site characterization and subsequent treatability studies. Once an understanding of various soil properties is obtained, the developer determines what alterations would make the soil ideal from a microbiological perspective, and selects an organic amendment formulation with the specific PSD and nutrient profile to effect these alterations. According to the developer, the DARAMEND™ Bioremediation Technology has been successfully applied to soils with widely different physical and chemical properties. For soils with high clay content DARAMEND™ organic soil amendments designed to prevent agglomeration (i.e., formation of large clods) are employed.

Since the partitioning of many soluble organic compounds between leached, adsorbed, and biodegraded fractions is influenced to some degree by textural variations, percent organic matter and moisture content of the soil, these physical parameters need to be defined during the initial site characterization. Soil moisture is particularly important, since excess moisture could limit the diffusion of oxygen through the soil matrix to microbially active microsites. Understanding the soil's WHC is also important in gaining insight on the irrigation requirements of the subject soil.

Chemical properties of the soil that are explored during site characterization/treatability studies include soil pH, macro- and micronutrient availability, the presence and concentration of inhibiting compounds (i.e., heavy metals, cyanide) and contaminant types and concentrations. Soil pH affects solubility, toxicity, adsorption, and volatilization of organic contaminants and ultimately the biotransformational capacity of the soil. A determination is made during this initial characterization as to whether soil pH has to be adjusted. The nutrient requirements necessary to sustain bacterial viability and growth are determined based on the mass of contaminants in the soil. These requirements are compared to the actual mass of nutrients available in the matrix. If the soil is lacking in the nutrients available for complete bioassimilation of the contaminant mass, more nutrients are added to the soil. The soil is sampled for toxic metals and any other compound that might be detrimental to the indigenous microbes. At elevated concentrations these compounds could negate the viability of bioremediation as a remedial alternative for these soils. The initial concentrations of PAHs and chlorophenols in the soils are also determined to assess if these concentrations have the potential to limit the rate at which biodegradation proceeds. Soils with extremely high concentrations of target contaminants might need to be mixed with soils having lesser amounts of contamination in order to optimize the conditions for biodegradation.

The presence of prolific indigenous microbial populations that utilize the organic contaminants as a food source is another potential operating parameter. Microbial activity is assessed prior to treatment and periodically during treatment as part of assessing the biotransformational capacities of the soil. Soil samples are collected over the course of the remediation to evaluate changes in the microbial populations resulting from system operation. Standard plate count methodologies are employed in the enumerations. In situations where the microbial populations are inadequate, the indigenous communities may be augmented with strains of hydrocarbon and PCP degrading microbes previously cultivated from the contaminated soil. The soil in the treatment plots did not require augmentation during the Demonstration.

Periodic soil tilling is an important operating aspect of the DARAMEND™ Bioremediation Technology. Following soil characterization and any treatability studies, the appropriate organic amendment formulation is tilled into the soil marking the start of treatment. The amendments selected are matched to the specific physical and chemical limitations of the soil to optimize biodegradation. The amendments are thoroughly mixed into the contaminated soil using specialized tilling equipment. The soil is tilled every two weeks and after each irrigation to increase diffusion of oxygen to the microsites and to ensure uniform distribution of irrigation water in the soil profile.

Maintaining the treated soil's moisture content after organic amendment addition is critical. After addition of the organic amendments, the WHC of the soil-amendment mixture is determined, and the irrigation requirements of the treated soil are established. WHC is an expression used to describe the mass of water that a soil can hold against the force of gravity. As long as a soil continues to retain water being added it is below 100% WHC. Saturation, or 100% of WHC, has been reached at this point where added water begins to be released from the soil. During remediation, the soil moisture content is maintained within a specified range (below the soil's WHC) to facilitate rapid growth of a large and viable microbial population. According to the developer, maintenance of soil moisture within a narrow range is critical for effective biodegradation of the target compounds. Excess soil moisture can impede the diffusion of oxygen through the soil matrix to microbially active microsites, due to a low ratio of air-filled to water-filled pores. If soil moisture falls below the optimum range, biodegradation can be inhibited due to inadequate biologically available water. Soil moisture is controlled by covering the treatment plots to eliminate wetting from precipitation. The frequency of irrigation is determined by weekly monitoring of soil moisture conditions at two depths: O-20 and 40-60 cm. The upper horizon is the zone where most of the water is consumed by microbial utilization, evaporation, and downward migration. The lower horizon is monitored for any excess soil moisture to appear. Taken together the two values allow effective characterization of the moisture status of the soil profile and thus indicate when irrigation is needed.

Soil temperature is monitored regularly because it can greatly influence the rate of bioremediation. Metabolic reactions tend to occur rapidly under warmer conditions and proceed more slowly under cooler conditions. In colder climates, the remediation season would be shorter, thereby extending the time it takes to remediate a site using the DARAMEND™ Bioremediation Technology. For an ex situ application, an enclosure that functions as a greenhouse can be constructed over the treatment plots to extend viable biodegradation into the winter months. Enclosures are typically not installed, since their construction adds substantially to the technology's capital cost, and the trade-off of reduced remediation time typically does not justify the construction expense.

To chart the progress of bioremediation using the DARAMEND™ Bioremediation Technology the developer periodically samples the treated soil. Sampling is performed by dividing the treatment area up into sample zones measuring 10 m on a side. Each sample zone is further subdivided into 1 m^2 sub-units. Soil homogenization due to frequent tilling negates the need to collect soils from every sub-unit. Typically, 5 sub-units from each sample zone are selected for sampling using a random number generator. Cores collected from each sub-unit within a single sample zone are homogenized together to form a single representative sample of that sample zone. Periodic sampling also allows the developer to determine if further adjustments to the physical and chemical properties of the soil are warranted.

2.3 Applicable Wastes

As of this writing, the DARAMEND™ Bioremediation Technology has been applied to six PAH- and PCP-contaminated soil sites in Canada. The DARAMEND™ Bioremediation Technology is considered suitable for the in situ and ex situ remediation of soil contaminated with PAHs and CPs, including PCP. These compounds (e.g., PCP and creosote) have been used in the treatment of wood because of their ability to inhibit or slow down the destruction of wood by microbes and other wood-infesting organisms. It is these same anti-microbial/bacterial characteristics that make bioremediation of soils contaminated with wood treatment chemicals difficult. The ability of the technology to reduce the acute toxicity of the soil's aqueous phase by transiently binding soil contaminants allows the process to treat soils typically considered too toxic for biodegradation. According to the developer, the technology has been proven on soils with PAH concentrations up to 18,500 mg/kg, total petroleum hydrocarbon concentrations up to 8,700 mg/kg, and PCP concentrations up to 660 mg/kg.

Soils with extremely high concentrations of target compounds have proved resistant to the DARAMEND™ Bioremediation Technology. Bench-scale testing conducted on soil with a PCP concentration of 18,000 mg/kg indicated that treatment was ineffective due to high acute soil toxicity. In these situations, the developer has diluted the highly contaminated soil with less contaminated soil to dilute the contaminants to a range more suitable for the DARAMEND™ Bioremediation Technology. The presence of certain inorganic compounds (heavy metals) at elevated concentrations may make a soil unsuitable for treatment using the DARAMEND™ Bioremediation Technology.

2.4 Availability and Transportability of the Equipment

The DARAMEND™ in situ and ex situ Bioremediation Technology is simple in design and implementation. The DARAMEND™ Bioremediation Technology is generally not considered to be a mobile technology because the process components are not trailer-mounted and are not capable of being transported from site to site. Most hardware components and materials needed to construct treatment plots are common and readily obtainable from local hardware/plumbing stores and lumber yards. Other equipment, including machinery, trailers, and storage sheds can often be rented locally. Utilizing rental equipment also tends to eliminate transportation needs and costs. Among the pieces of equipment that might be required are dump trucks, rotary tillers, front-end loaders, mechanical shaker screens, backhoes, excavators, skid-steer loaders, graders, fork lifts, electrical generators, and steam cleaners. The DARAMEND™ Bioremediation Technology is assembled onsite with basic hardware and plumbing components that can be transported to the site in vehicles no larger than a pick-up truck. The only supplies that might have to be brought in are the soil amendments and some laboratory and sampling items. Given these features, the DARAMEND™ Bioremediation Technology is always available.

System installation can take from a week to a month. The time it takes to set up an ex situ system depends on the volume of soil to be processed, the distance that the soil has to be transported, and the size of the treatment plots. An in situ system takes considerably less time to get started since no construction is involved and the soil does not have to be excavated and screened. The initial soil characterization and any treatability studies would likely be conducted concurrently or prior to system installation.

System demobilization activities would consist of disconnecting utilities, disassembling the treatment plots, returning treated soil to its original location, regrading, decontaminating equipment, and arranging for disposal of all residuals. Large debris that is initially screened from the soil will need to be handled, stored, and disposed of as hazardous waste.

2.5 Materials Handling Requirements

The DARAMEND™ Bioremediation Technology involves a certain amount of materials handling; the ex situ application more so than the *in situ* application. For ex situ treatment, contaminated soil must be excavated, screened, homogenized, and if the initial concentrations are too high, diluted with less contaminated soil. *In situ* treatment requires only that the soil be homogenized. Both applications require the incorporation of organic amendments into the soil using tilling equipment. Depending on terrain features and the volume of soil to be treated, site and soil preparation can involve any combination of dump trucks, front-end loaders, backhoes, excavators, conveyors, skid-steer loaders, graders, and fork lifts, in addition to a power take-off rotary tiller. Screening equipment (Le., subsurface combs, portable vibrating screen, etc.) is often required for both *in situ* and ex situ treatment to remove coarse material in the soil (e.g., cobbles, large pieces of wood and metal, other debris) that would interfere with the incorporation of the amendments. In addition, ex situ treatment also involves the construction of a contained treatment cell consisting of a bermed concrete pad or a plastic liner/fibrepad/sand layer configuration prior to delivery of the contaminated soil. Once the soil is properly prepared and delivered to the treatment cell, the physical and chemical properties of the soil will be defined during the initial waste characterization. Regular tilling initially distributes the organic amendments through the soil. Afterwards, the soil is tilled every two weeks or immediately after irrigation to increase oxygen to microsites and ensure uniform distribution of irrigation water in the soil profile.

The DARAMEND™ Bioremediation Technology is designed to limit the production of leachate. Although controls are in place to limit excessive soil wetting due to rainfall/snow melt, extreme weather conditions can cause problems. The ex *situ* treatment plots are lined with HDPE and are contoured in a manner that would direct any leachate along the central axis of the plot for collection. Any leachate that is collected must be disposed of according to regulatory criteria or slowly recycled back into the plot as irrigation make-up water.

After treatment, the ex situ treatment plots are disassembled and consumable items, such as the polyethylene sheeting, fiberpad, and plot covers must be disposed of. Large debris that was initially screened from the soil will need to be handled, stored, and disposed of as hazardous waste. Treated soils can remain onsite, if they satisfy site-specific ARARs.

2.6 Site Support Requirements

Technology support requirements include utilities, support facilities, and support equipment. These requirements are discussed below.

The DARAMENDTM Bioremediation Technology does not require any major utilities to operate. Minor utilities needs include electricity, a potable water supply, telephone, and sewer service. Electricity with 110 volt service is needed to supply power to a laboratory/field trailer. If power is unavailable and a connection to the power grid is considered unfeasible, electric generators would likely satisfy any power requirements. Water is necessary for soil irrigation, equipment decontamination, laboratory uses, and personnel consumption. If potable water is unavailable, it can be trucked in and stored onsite. Phone service to the site would allow the field trailer to operate as a satellite office and would promote more efficient project administration functions. Phone service is also important in summoning emergency assistance. If a sewer connection is not available, portable toilets can be used for sanitary purposes.

Support facilities required by the DARAMEND™ Bioremediation Technology include a laboratory/field trailer and a storage shed for storing amendments, supplies, and tools. A roll-off or drum storage area is required for the temporary storage of screened debris generated during soil preparation. An assortment of heavy equipment, discussed in Section 2.5, is required during treatment setup and decommissioning.

Access to the site must be provided over roads suitable for travel by heavy equipment. Personnel must also be able to reach the site without difficulty. Depending on site location, security measures might be necessary to protect the public from accidental injury and to prevent accidental or intentional damage to the developer's equipment. A chain link fence with a locking gate large enough to allow trucks to enter and leave should provide adequate security.

2.7 Ranges of Suitable Site Characteristics

To date, the DARAMEND™ Bioremediation Technology has been applied to total petroleum hydrocarbons (TPH), PAH, and chlorinated phenol contaminated soils at wood treating facilities. This report represents a critical step in the development and commercialization of a treatment technology.

The site should be well graded and accessible to an assortment of heavy equipment such as dump trucks, front-end loaders, backhoes, excavators, skid-steer loaders, graders, fork lifts and a rotary tiller. Areas that are designated for excavated or *in situ* treatment must be free of utilities lines or other underground features (i.e., fuel tanks, piping). The subsurface should be free of large debris, such as might be found in a landfill.

Areas designated for the staging of ex situ treatment plots must satisfy the space requirements of the treatment plots. Since the depth of the soil deposited in a treatment plot is dictated by the limitations of the tilling equipment, approximately 20 m^2 of surface area are necessary to treat 10 m^3 of contaminated soil. Tilling equipment can only mix soils to a depth of 0.5 m. The maximum tilling depth also imposes limitations on the *in situ* application of the technology. If contamination extends to greater depths, a possible option is to treat the soil 0.5 m at a time, whereby the treated soil is temporarily removed to expose the next layer of contaminated soil. However, remediating the site a layer at a time will increase the throughput time. For *in situ* treatment, any dimension plot can be treated; however, in addition to the depth limitation previously discussed, any *in situ* plot should be free of obstruction that could interfere with tilling equipment. Other space requirements include an area large enough to set up a laboratory/field trailer and a drum staging or roll-off storage area. Sufficient space should be available to maneuver the trailer and roll-off in and out of the site, and there should be room for a wastewater storage tank and a tank truck if potable water needs to be trucked in. Enough space for a small shed used to store organic amendments and tools should also be available. A small area, measuring 4 m^2, is needed to facilitate the decontamination of equipment and personnel throughout the remediation.

Since the DARAMEND™ Bioremediation Technology physically and chemically alters the contaminated soil to enhance the rate of bioremediation, soil characteristics at a particular site are not as critical in determining a site's suitability for the DARAMEND™ Bioremediation Technology as they might be for other bioremediation technologies. A number of factors that could interfere with the process would be an inordinate amount of debris in the soil, that would interfere with the incorporation of organic amendments and reduce the effectiveness of tilling, and the presence of toxic compounds (i.e., heavy metals) that may be detrimental to soil microbes. In addition, soils with a high humic content could interfere with the application of the DARAMEND™ Bioremediation Technology by slowing down the cleanup through increased organic adsorption and oxygen demand.

Sites that are suitable for the DARAMEND™ Bioremediation Technology should not be prone to seasonal flooding nor have a water table that fluctuates to within 1 m of the site's surface. A high water table and flooding will interfere with attempts to maintain soil moisture within the narrow range necessary for effective biodegradation and could potentially redistribute contamination across the site. Flooding could also destroy the ex *situ* treatment plots, equipment, and supplies.

The DARAMEND™ Bioremediation Technology is suitable for organic contaminants found in wood preserving soils, such as PAHs and CPs. The developer has also reported encouraging results with soils contaminated with light oils, heavy oils, and phthalates. The developer has indicated that the technology would experience problems with soils contaminated with PCBs. In addition, soils with extremely high contaminant levels may limit the rate at which biodegradation proceeds, and would need to be mixed with less contaminated soil to allow biodegradation to proceed.

The technology can be operated in nearly every climate, although remediation times are extended in colder climates due to a significant reduction in the rates of remediation during the winter months. A canopy placed over the treatment plot to prevent excessive soil wetting by precipitation also insulates the soil to some degree.

The DARAMEND™ Bioremediation Technology can be used in fairly close proximity to inhabited areas, providing that appropriate measures are implemented to prevent offsite emissions, odors, and noise. The DARAMEND™ Bioremediation Technology generates very little noise, since the plots are left idle for the majority of the treatment period. Some noise will be generated during the initial phases of remediation that will involve excavation and tilling of the soil. Additional noise would be generated when the soil is retilled every other week. Precautions might need to be taken at some sites to limit the production of volatile emissions and dust during excavation and tilling.

2.8 Limitations of the Technology

The ex *situ* DARAMEND™ Bioremediation Technology is similar to landfarming technologies in that a large amount of space is required to treat the soils. Fortunately, most work to date has been done on former wood preserving sites, which by nature have plenty of land available. The land requirements of the technology are exacerbated by the limitations of the tilling equipment, which can only till soil down to a depth of 0.6 m. As a result, the surface dimensions of a treatment plot are enlarged to compensate for the depth limitations. The tillage equipment also limits the depth to which soil can be remediated in the *in situ* application of the technology. The *in situ* treatment plot must also be free of any surface and subsurface obstructions that would interfere with soil tilling.

The ex *situ* application of the DARAMEND™ Bioremediation Technology requires soil to be excavated from one area and treated in another area. Communities generally prefer technologies that do not require excavation due to the noise and potential emissions that are produced. Communities also object to the inherent hazards associated with increased heavy equipment and truck traffic in their neighborhoods.

At some sites the reduction of contaminant concentrations may be caused more by volatilization than biodegradation. This problem has not been encountered yet, since the technology has only been applied to soil contaminants characterized by low volatility. If the technology is applied to a site where the contaminants consist primarily of lighter, more volatile compounds a significant percentage of the contaminant mass will be volatilized as a result of soil handling. It is likely that certain controls would have to be implemented at sites where soils are contaminated primarily with volatile organic contaminants, in order to meet air quality standards.

The DARAMEND™ Bioremediation Technology appears to be limited to soils contaminated with non-halogenated and slightly halogenated organic compounds. The developer claims that the technology would probably not work on soils contaminated with PCBs or highly halogenated organics. In addition, the DARAMEND™ Bioremediation Technology is a soil remediation system and does not treat ground water, surface water, or sludge.

2.9 ARARS for the DARAMEND™ Bioremediation Technology

This subsection discusses specific federal environmental regulations pertinent to the operation of the DARAMEND™ Bioremediation Technology including the transport, treatment, storage, and disposal of wastes and treatment residuals. Federal and state applicable or relevant and appropriate requirements (ARARs) are presented in Table 2-l. These regulations are reviewed with respect to the demonstration results. State and local regulatory requirements, which may be more stringent, must also be addressed by remedial managers. ARARs include the following: (1) the Comprehensive Environmental Response, Compensation, and Liability Act; (2) the Resource Conservation and Recovery Act; (3) the Clean Air Act; (4) the Safe Drinking Water Act; (5) the Toxic Substances Control Act; and (6) the Occupational Safety and Health Administration regulations. These six general ARARs are discussed below.

2.9.1 *Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)*

The CERCLA of 1980 as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986 provides for federal funding to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or to the environment.

As part of the requirements of CERCLA, the EPA has prepared the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) for hazardous substance response. The NCP is codified in Title 40 Code of Federal Regulations (CFR) Part 300, and delineates the methods and criteria used to determine the appropriate extent of removal and cleanup for hazardous waste contamination.

SARA states a strong statutory preference for remedies that are highly reliable and provide long-term protection and directs EPA to do the following:

- Use remedial alternatives that permanently and significantly reduce the volume, toxicity, or mobility of hazardous substances, pollutants, or contaminants.
- Select remedial actions that protect human health and the environment, are cost effective, and involve permanent solutions and alternative treatment or resource recovery technologies to the maximum extent possible.
- Avoid offsite transport and disposal of untreated hazardous substances or contaminated materials when practicable treatment technologies exist [Section 121 (b)].

The DARAMEND™ Bioremediation Technology meets each of these requirements. Volume, toxicity, and mobility of contaminants in the waste matrix are all reduced as a result of treatment. Organic compounds are biodegraded by indigenous soil microbes either *in situ* or ex situ in a series of specially designed treatment plots. In both cases, contaminants are subject to biochemical reactions that convert them to cell material and energy for metabolic processes. Even though microbial, biochemical byproducts of these reactions were not monitored during the demonstration, they were assumed to consist of carbon dioxide and water. Except for the debris that is screened from the soil prior to treatment, the need for offsite transportation and disposal of solid waste is eliminated by *in situ* treatment. Soils, once treated, can be left in place. Volatile emissions generated during construction and tilling operations might require control and treatment prior to release to the atmosphere.

In general, two types of responses are possible under CERCLA: removal and remedial action. Superfund removal actions are conducted in response to an immediate threat caused by a release of hazardous substances. Removal action decisions are documented in an action memorandum. Many removals involve small quantities of waste or immediate threats requiring quick action to alleviate the hazard. Remedial actions are governed by the SARA amendments to CERCLA. As stated above, these amendments promote remedies that permanently reduce the volume, toxicity, and mobility of hazardous substances, pollutants, or contaminants. The DARAMEND™ Bioremediation Technology is likely to be part of a CERCLA remedial action.

Onsite remedial actions must comply with federal and more stringent state ARARs. ARARs are determined on a site-by-site basis and may be waived under six conditions: (1) the action is an interim measure, and the ARAR will be met at completion; (2) compliance with the ARAR would pose a greater risk to health and the environment than noncompliance; (3) it is technically impracticable to meet the ARAR; (4) the standard of performance of an ARAR can be met by an equivalent method: (5) a state ARAR has not been consistently applied elsewhere; and (6) ARAR compliance would not provide a balance between the protection achieved at a particular site and demands on the Superfund for other sites. These waiver options apply only to Superfund actions taken onsite, and justification for the waiver must be clearly demonstrated.

2.9.2 *Resource Conservation and Recovery Act (RCRA)*

RCRA, an amendment to the Solid Waste Disposal Act (SWDA), is the primary federal legislation governing haz-

Table 2-1. Federal and State Applicable and Relevant and Appropriate Requirements (ARARs) for the DARAMEND™ Bioremediation Technology

Process Activity	ARAR	Description of Regulation	General Applicability	Specific Applicability to DARAMEND™
Waste Characterization of untreated wastes	RCRA: 40 CFR Part 261 or state equivalent	Standards that apply to identification and characterization of wastes	Chemical and physical analyses must be performed to determine if waste is a hazardous waste.	Chemical and physical properties of waste determine its suitability for treatment by DARAMEND™
Soil excavation	CAA: 40 CFR Part 50 (or state equivalent)	Regulations govern toxic pollutants, visible emissions and particulates	If excavation is performed, emission of volatile compounds or dusts may occur.	Applied to construction activities (i.e., excavation and screening) during system installation
	RCRA: 40 CFR Part 262 or state equivalent	Standards that apply to generators of hazardous waste	Excavated soils may be considered hazardous waste.	Staged soil for ex situ treatment should be placed in treatment plots immediately
Storage prior to processing	RCRA: 40 CFR Part 264 or state equivalent	Standards applicable to the storage of hazardous waste	Excavation and pretreatment screening may generate hazardous oversized wastes that must be stored in waste piles.	If stored in a waste pile, the materials should be placed on and covered with plastic, and tied down to minimize fugitive emissions. The time between excavation and treatment (or disposal if material is unsuitable for treatment) should be minimized
Waste processing	RCRA: 40 CFR Part 264 (or state equivalent)	Standards that apply to treatment of wastes in a treatment facility	When hazardous wastes are treated, there are requirements for operations, recordkeeping, and contingency planning.	Applicable or appropriate for DARAMEND™ operations
Waste processing	CAA: 40 CFR Part 50 (or state equivalent)	Regulation governs toxic pollutants, visible emissions. and particulates	Stack gases may contain volatile organic compounds, or other regulated gases	During the SITE Demonstration, no stack gases were emitted, however, stack gases may be of concern and must not exceed limits set for the air district of operation. Standards for monitoring and recordkeeping apply
Storage of auxiliary wastes	RCRA: 40 CFR Part 264 Subpart J (or state equivalent)	Regulation governs standards for tanks at treatment facilities	If storing non-RCRA wastes, RCRA requirements may still be relevant and appropriate	Storage tanks for liquid wastes (e.g., decontamination waters and condensate) must be placarded appropriately, have secondary containment, and be inspected daily
	RCRA: 40 CFR Part 264 Subpart I (or state equivalent)	Regulation covers storage of waste materials generated	Applicable for RCRA wastes; relevant and appropriate for non-RCRA wastes	Roll-offs or drums containing drill cuttings need to be labeled as hazardous waste. The storage area needs to be in good condition, weekly inspections are required, and storage should not exceed 90 days unless a storage permit is obtained

(continued)

Table 2-1 Continued

Process Activity	ARAR	Description of Regulation	General Applicability	Specific Applicability to DARAMEND™
Waste characterization (treated waste)	RCRA: 40 CFR Part 261 (or state equivalent)	Standards that apply to identification and characterization of wastes	Chemical and physical analyses must be performed to determine if treated waste is a hazardous waste.	Chemical and physical properties of treatment residuals must be performed prior to disposal.
Storage after treatment	RCRA: 40 CFR Part 264 Subpart I (or state equivalent)	Standards that apply to the storage of hazardous waste	The treated material will be stored in the plot until it has been characterized and a decision on final disposition has been made.	The treatment plots must be maintained. If stored in a waste pile, oversize material should be placed on and covered with plastic, and tied down to minimize fugitive emissions. The material should be disposed of or otherwise treated as soon as possible.
Waste disposal	RCRA: 40 CFR Part 262	Standards that pertain to generators of hazardous waste	Generators must dispose of wastes at facilities that are permitted to handle the waste. Generators must obtain an EPA ID number prior to waste disposal.	Waste generated by the DARAMEND™ is limited to contaminated drill cuttings. Spent activated carbon could be another waste if carbon is used in the treatment of system off gases.
	CWA: 40 CFR Parts 403 and/or 122 and 125	Standards for discharge of wastewater to a POTW or to a navigable waterway	Discharge of wastewaters to a POTW must meet pretreatment standards; discharges must be permitted under NPDES.	Applicable and appropriate for decontamination wastewaters and condensate.
	RCRA: 40 CFR Part 268	Standards regarding land disposal of hazardous wastes	Hazardous wastes must meet specific treatment standards prior to land disposal, or must be treated using specific technologies.	The treated material will be stored in the treatment plot until it has been characterized and a decision on final disposition has been made.

ardous waste activities and was passed in 1976 to address the problem of how to safely dispose of municipal and industrial solid waste. Subtitle C of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste, most of which are also applicable to CERCLA activities. The Hazardous and Solid Waste Amendments (HSWA) of 1984 greatly expanded the scope and requirements of RCRA.

RCRA regulations define hazardous wastes and regulate their transport, treatment, storage, and disposal. If soils are determined to be hazardous according to RCRA (either because of a characteristic or a listing carried by the waste), all RCRA requirements regarding the management and disposal of hazardous waste must be addressed by the remedial managers. Criteria for identifying characteristic hazardous wastes are included in 40 CFR Part 261 Subpart C. Listed wastes from specific and nonspecific industrial sources, off-specification products, spill clean-ups, and other industrial sources are itemized in 40 CFR Part 261 Subpart D. If the Domtar demonstration site was located within the United States, the technology would likely be subject to RCRA regulations because the former wood treatment facility would be contaminated with RCRA-listed wastes included under the F034 code (e.g., wastewaters, process residuals, preservative drippage, and spent formulations from wood preserving processes generated at plants that use creosote formulations). RCRA regulations do not apply to sites where RCRA-defined hazardous wastes are not present.

Unless they are specifically delisted through delisting procedures, hazardous wastes listed in 40 CFR Part 261 Subpart D remain listed wastes regardless of the treatment they may undergo and regardless of the final contamination level in the streams and residues. This implies that even after remediation, “clean” wastes are still classified as hazardous because the pretreatment material was a listed waste.

For generation of any hazardous waste, the site responsible party must obtain an EPA identification number. Other applicable RCRA requirements may include a Uniform Hazardous Waste Manifest (if the waste is transported), restrictions on placing the waste in land disposal units, time limits on accumulating waste, and permits for storing the waste.

Requirements for corrective action at RCRA-regulated facilities are provided in 40 CFR Part 264, Subpart F (promulgated) and Subpart S (partially promulgated). These subparts also generally apply to remediation at Superfund sites. Subparts F and S include requirements for initiating and conducting RCRA corrective action, remediating ground water, and ensuring that corrective actions comply with other environmental regulations. Subpart S also details conditions under which particular RCRA requirements may be waived for temporary treatment units operating at corrective action sites and provides information regarding requirements for modifying permits to adequately describe the subject treatment unit.

2.9.3 Clean Air Act (CAA)

The CAA establishes national primary and secondary ambient air quality standards for sulfur oxides, particulate matter, carbon monoxide, ozone, nitrogen dioxide, and lead. It also limits the emission of 189 listed hazardous pollutants such as vinyl chloride, arsenic, asbestos, and benzene. States are responsible for enforcing the CAA. To assist in this, Air Quality Control Regions (AQCR) were established. Allowable emission limits are determined by the AQCR, or its sub-unit, the Air Quality Management District (AQMD). These emission limits are determined based on whether or not the region is currently within attainment for National Ambient Air Quality Standards (NAAQS).

The CAA requires that treatment, storage, and disposal facilities comply with primary and secondary ambient air quality standards. Fugitive emissions from the DARAMEND™ Bioremediation Technology may come from (1) excavation and construction of ex situ treatment plots, (2) periodic tilling of soil in ex situ and *in situ* treatment plots, and (3) the staging and storing of screened debris. Soil moisture should be managed during system installation to prevent or minimize the impact from fugitive emissions. State air quality standards may require additional measures to prevent fugitive emissions.

2.9.4 Clean Water Act (CWA)

The objective of the CWA is to restore and maintain the chemical, physical, and biological integrity of the nation's waters. To achieve this objective, effluent limitations on toxic pollutants from point sources were established. Publicly-owned treatment works (POTWs) can accept wastewaters with toxic pollutants; however the facility discharging the wastewater must meet pretreatment standards and may need a discharge permit. A facility desiring to discharge water to a navigable waterway must apply for a permit under the National Pollutant Discharge Elimination System (NPDES). When an NPDES permit is issued, it includes waste discharge requirements according to volume and contaminant concentration.

The only wastewater produced by the DARAMEND™ Bioremediation Technology that might need to be managed is wastewater generated during equipment decontamination. Soil moisture in the treatment plots is controlled within strict limits to optimize biodegradation and prevent the generation of leachate. Leachate could also be generated as a consequence of rainwater or snow melt seeping through a treatment plot cover. Decontamination water could amount to several thousand gallons depending on the scale of a remediation effort at a given site. Depending on the levels of contaminants and the volume of this wastewater, pretreatment might be required prior to discharge to a POTW. This water could possibly be used as makeup water for spray irrigation of the treatment plots thereby eliminating the need for disposal at a POTW.

2.9.5 Safe Drinking Water Act (SDWA)

The SDWA of 1974, as most recently amended by the Safe Drinking Water Amendments of 1986, requires EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorized national drinking water standards and a joint federal-state system for ensuring compliance with these standards.

The National Primary Drinking Water Standards are found in 40 CFR Parts 141 through 149. These drinking water standards are expressed as maximum contaminant levels (MCLs) for some constituents, and maximum contaminant level goals (MCLGs) for others. Under CERCLA (Section 121 (d)(2)(A)(ii)), remedial actions are required to meet the standards of the MCLGs when relevant. The DARAMEND™ Bioremediation Technology is not agroundwater remediation technology, but it could improve the quality of the ground water by reducing contaminant loading by bioremediating the source of contamination in the vadose zone.

2.9.6 Toxic Substances Control Act (TSCA)

The TSCA of 1976 grants EPA the authority to prohibit or control the manufacturing, importing, processing, use, and disposal of any chemical substance that presents an unreasonable risk of injury to human health or the environment. These regulations may be found in 40 CFR Part 761; Section 6(e) deals specifically with PCBs. Materials with less than 50 ppm PCB are classified as non PCB; those containing between 50 and 500 ppm are classified as PCB-contaminated; and those with 500 ppm PCB or greater are classified as PCB. PCB-contaminated materials may be disposed of in TSCA-permitted landfills or destroyed by incineration at a TSCA-approved incinerator; PCBs must be incinerated. Sites where spills of PCB-contaminated material or PCBs have occurred after May 4, 1987, must be addressed under the PCB Spill Cleanup Policy in 40 CFR Part 761, Subpart G. The policy establishes cleanup protocols for addressing such releases based upon the volume and concentration of the spilled material. To date, it has not been documented that the DARAMEND™ Bioremediation Technology is useful for PCB-contaminated wastes.

2.9.7 Occupational Safety and Health Administration (OSHA) Requirements

CERCLA remedial actions and RCRA corrective actions must be performed in accordance with the OSHA requirements detailed in 20 CFR Parts 1900 through 1926, especially §1910.120, which provides for the health and safety of workers at hazardous waste sites. Onsite construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part 1926 of OSHA, which describes safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than federal standards, must also be met.

All technicians and subcontractors involved with the construction and operation of the DARAMEND™ Bioremediation Technology will be required to have completed an OSHA training course and be familiar with all OSHA requirements relevant to hazardous waste sites. Workers on hazardous waste sites must also be enrolled in a medical monitoring program. The elements of any acceptable program must include (1) a health history, (2) an initial exam before hazardous waste work starts to establish fitness for duty and a medical baseline, (3) periodic examinations (usually annual) to determine whether changes due to exposure may have occurred and to ensure continued fitness for the job, (4) appropriate medical examinations after a suspected or known overexposure, and (5) an examination at termination.

For most sites, minimum personal protective equipment (PPE) for workers will include gloves, hard hats, safety glasses, steel-toe boots, and Tyvek®. Depending on contaminant types and concentrations, additional PPE may be required, including the use of air purifying respirators or supplied air. Noise levels during the construction and operation of the DARAMEND™ Bioremediation Technology are not expected to be high, except during the construction, which will involve the operation of heavy equipment. During these activities, noise levels should be monitored to ensure that workers are not exposed to noise levels above a time-weighted average of 85 decibels over an eight-hour day. If noise levels increase above this limit, workers will be required to wear ear protection. The levels of noise anticipated are not expected to adversely affect the community, depending on its proximity to the treatment site.

Workers will be required to comply with the recently promulgated OSHA requirements for confined spaces (29 CFR §1910.146), including requirements for stand-by personnel, monitoring, placarding, and protective equipment. Since the construction phase of DARAMEND™ Bioremediation Technology will require some excavation, trenches could be considered confined spaces (based on type and depth). Other construction- or plant-related OSHA standards may also apply while installing and managing the DARAMEND™ Bioremediation Technology, including shoring of trenches, and lock-out/tag out procedures on powered equipment.

2.9.8 State Requirements

In many cases, state requirements supersede the corresponding federal program, such as OSHA or RCRA, when the state program is federally approved and the requirements are more strict.

Section 3
Economic Analysis

3.1 Introduction

This economic analysis is based primarily on results and experiences gained from the SITE demonstration that was conducted over an 11-month period at the Domtar Wood Preserving Facility located in Trenton, Ontario, Canada. The costs associated with treatment by the GRACE Bioremediation Technologies DARAMEND™ Bioremediation Treatment Technology, as presented in this economic analysis, are defined by 12 cost categories that reflect typical cleanup activities performed at Superfund sites. Each of these cleanup activities is defined and discussed. Many of the cost assumptions are derived from information supplied by GRACE Bioremediation Technologies, based on a full-scale remediation project at the Domtar facility and other field projects conducted in Canada. Certain assumptions and costs are also based on previous experience with similar bioremediation processes evaluated under the SITE Program. Collectively, they form the basis for a cost analysis of a full-scale remediation using this technology at the Domtar facility.

The GRACE Bioremediation Technologies DARAMEND™ Bioremediation Treatment Technology is principally applicable to wood preserving soils and sediments contaminated with organic wood preserving compounds, such as PCP and PAH constituents of creosote. A number of factors could affect the cost of treatment. Among them are soil type, contaminant type and concentration, soil moisture, geographic location, site size and accessibility, required support facilities and utilities, and treatment goals. It is important to thoroughly and properly characterize the site before implementing this technology, to determine the amount and type of amendment to add, and to decide whether a leachate collection, storage, and treatment system is needed. Although this characterization cost may be substantial, it is not included here. It is also highly recommended that a treatability study be performed so that the amendment that would be most effective at a particular site can be identified and its respective dosage level determined. The cost for this is also not included here.

An economic analysis for a full-scale remediation at this site was done for an in situ and an ex situ case, assuming the process was implemented in a similar manner with similar performance to that demonstrated under the SITE Program. Cost figures provided here are "order-of-magnitude" estimates and are generally +50/-30%.

3.2 Conclusions

- A full-scale cleanup of this site using this technology was estimated to cost between \$619,000 for an in situ plot with an attendant unit cost of \$92/m³ (\$70/yd³), and \$959,000 for an ex situ plot with an attendant unit cost of \$140/m³ (\$108/yd³), including the cost of residual disposal. The residual consisted of oversized particles screened out of the soil during pretreatment and deemed to be hazardous. Landfilling was assumed to be the preferred disposal option, although this may not be permissible for these types of wastes in some jurisdictions.

- Without residual disposal, the unit costs decrease to \$46/m³ (\$35/yd³) for the *in situ* plot, representing a 50% reduction, and \$96/m³ (\$73/yd³) for the ex *situ* plot, representing a 31% reduction.

- In either case, the *in situ* plot was far more economical to set up and operate than the ex *situ* plot. However, there are instances where ex *situ* treatment may be more advantageous than *in situ* treatment, particularly for highly toxic or recalcitrant soils. Better control over moisture content and temperature can be achieved, resulting in more uniform treatment without isolated pockets of high concentration soils.

- For both cases, residuals and waste shipping and handling was the predominant cost category (51% for the *in situ* case and 35% for the ex *situ* case).

- No costs were assigned for effluent treatment and disposal because the SITE demonstration results showed that no leachate was generated for the ex *situ* case. This was also assumed to be the case for the *in situ* plot, although the developer has indicated that pilot-scale testing would be required at other sites because it is a highly site-specific phenomenon.

- For the *in situ* plot, startup (22%), site preparation (II%), and labor (8%) were the next largest categories; together with residuals and waste shipping and handling, they account for over 90% of the total cost.

- For the ex situ plot, residual and waste shipping and handling costs were followed by labor (29%), site preparation (18%), and consumables and supplies (1 0%), again accounting for over 90% of the total.

- For both plots, labor and site preparation were among the top four cost categories. In the case of the ex situ plot, this is related to the construction of the treatment pad, the purchase and installation of the greenhouse, the additional labor connected with multiple treatment cycles, and the longer treatment times associated with a smaller plot. For the in situ plot, these costs are a reflection of the larger plot size assumed.

- Costs attributed to analytical services, capital equipment, demobilization, and permitting and regulatory requirements are about the same forboth plots. This indicates that these categories do not appear to depend on whether an *in situ* or ex situ process is selected.

3.3 Issues and Assumptions

This section summarizes the major issues and assumptions used. In general, assumptions are based on information provided by the developer and observations made during this and other SITE demonstration projects.

3.3.1 *Waste Volumes and Site Size*

This economic analysis assumes that the site and wastes have already been thoroughly and properly characterized, and that these results were used to optimize the DARAMEND™ Bioremediation Technology, i.e., the type and amount of contaminants present, the heterogeneity of the soil, the type and amount of amendment to add, etc. Therefore, it does not include the costs for treatability studies, waste characterization tests, pilot studies, or process optimization. All of these activities could add substantially to costs and time required for remediation.

The volume of soil to be treated was estimated to be 6,800 m^3 (8,900 yd^3). Two scenarios were considered. The first was *in situ* treatment of the contaminated soil without excavation; the second was above ground treatment in a fabricated plot contained in a greenhouse, hereafter referred to as the ex situ case. For both cases, treatment down to a depth of 0.6 m (2 ft) was assumed. For the ex situ case, a half-acre plot (2,300 m^2, 25,000 ft^2) was assumed, containing two parallel plots each covered by a greenhouse. This scenario would require five treatment cycles to treat the entire volume of waste. For the *in situ* plot, the entire volume of waste was assumed to be treated in a single 1 l-month period. This would require an area of 11,400 m^2 (123,000 ft^2) or 2.8 acres. Smaller or larger *in situ* batches could be treated depending on the site physical constraints and the client requirements. Use of a greenhouse cover depends as much on the physical shape of the treatment area as the size of the area.

3.3.2 Process Optimization and Performance

The performance of a full-scale system for both scenarios considered here was assumed to be similar to the ex situ case demonstrated under the SITE Program. Results from the SITE demonstration indicated that PCP concentrations were reduced 88%, PAH concentrations were reduced 94%, and TRPH concentrations were reduced 87% over an 11 -month period that included a full winter season. Although the developer fell slightly shy of its claims, it was assumed that treatment goals would have been attained had the demonstration gone on for a full 12 months.

Since better control over the bioremediation process can be maintained in a greenhouse, the ex situ plot could treat the same soil in less time than the *in situ* plot. Furthermore, the ex situ plot could treat more recalcitrant soils with higher initial contaminant concentrations in the same period of time. For this analysis, the latter was assumed. For the *in situ* plot, GRACE Bioremediation Technologies measured the average initial PAH concentration to be 77 mg/kg and the average initial PCP concentration to be 6 mg/kg. The ex situ plot, on the other hand, had an average initial PAH concentration of 500 mg/kg and an average initial PCP concentration of 125 mg/kg. For purposes of this analysis, it was assumed that the *in situ* plot would achieve similar performance levels due to lower starting contaminant concentrations. The tacit assumption is that this level of removal would be sufficient to meet regulatory standards.

3.3.3 Process Operating Requirements

For this bioremediation technology, the majority of activity occurred either during site preparation and startup or during demobilization. For the ex situ case, involving multiple treatment cycles, there is additional labor between cycles to remove the treated soil and replace it with contaminated soil for the next treatment cycle. As will be discussed in more detail later, this effort involves manpower as well as the necessary equipment and materials. These have all been lumped into a single hourly rate that will be referred to in the text as the labor, equipment, and material (LE&M) rate. This rate was used in the startup and demobilization cost categories.

For the ex situ case, this LE&M rate was also used as a separate line item under the labor cost category entitled ‘Changeover.“This represents the work effort involved between treatment cycles to excavate cleaned soil and replace it with contaminated soil. For both *in situ* and ex situ cases, another line item entitled “Maintaining Treatment” was used to reflect the manpower requirements for plot maintenance. These tasks would include monitoring soil physical and chemical properties (i.e., moisture, pH, temperature), irrigating to maintain target soil moisture content, tilling to ensure a homogeneous and aerated soil mass, and inspecting the site regularly. Routine equipment maintenance could also be done by the plot maintenance people already onsite.

SITE demonstration results from the ex situ plot indicated that no leachate was generated. This was also assumed to be the case with the *in situ* plot. To determine whether this would be true for other *in situ* applications, GRACE Bioremediation Technologies would probably conduct ex situ pilot tests before designing a full-scale remediation system. Consequently, the cost of leachate collection and treatment was not included for either the *in situ* or ex situ case.

3.3.4 *Financial Assumptions*

All costs are given in U.S. dollars, without accounting for interest rates, inflation, or the time value of money. Insurance and taxes are assumed to be fixed costs listed under "Startup" and are calculated as 10% of annual capital equipment costs.

3.4 Basis for Economic Analysis

In order to compare the cost effectiveness of technologies in the SITE Program, EPA breaks down costs into the 12 categories shown in Table 3-1, using the general assumptions already discussed. The assumptions used for each cost factor are discussed in more detail below.

3.4.1 *Site Preparation*

The amount of preliminary preparation necessary for bioremediation technologies is highly site-specific. For this analysis, generic site preparation responsibilities such as site design and layout, surveys and site logistics, legal searches, access rights and roads were all assumed to be performed by the responsible party (or site owner) in conjunction with the developer. None of these costs have been included here.

The focus instead was on technology-specific activities. These included treatment plot fabrication, utility connections, trailer rentals, fence installation, and where appropriate, greenhouse construction (Table 3-2). These are generally one-time charges and are necessarily site-specific. In the case of the ex situ plot, there may be recurring charges associated with replacing the sand layer and repairing the polyethylene liner and/or the fiberpad. When treated soil is removed from the plot some of the sand may be removed, and damage to the liner and/or fiberpad may occur. Hence, replacements may be necessary. This cost is included under Maintenance and Modifications. Since the treatment depth was assumed to be the same as that in the SITE demonstration, 0.6 m (2 ft), costs were based on area rather than volume.

Treatment plot fabrication costs were assumed to consist of two components, earth work and treatment plot preparation (Table 3-2). Earth work involved the cleaning of debris and brush, and the grading of soil. Both plots would require this step and costs were estimated using the following formula from the developer:

$$\$5,000 + \$5,000 \ (A \ / \ 1,500 \ m^2)$$

where A is the area of the plot in m^2. This is justified by the fact that the contractor used to do these tasks and usually required a minimum charge of $5,000 just to mobilize his equipment and bring it onsite, regardless of the site size. The second term represents the cost to perform these tasks based on $5,000/1 ,500$m^2$. The result of this calculation was rounded up to nearest $5,000 to get a conservative estimate.

For the ex situ plot, an additional component is required to account for preparation and installation of a 1 Ocm (4 in.) thick sand buffer zone, a 4mm thick fiberpad, a polyethylene liner, and another 15cm (6 in.) thick sand layer. The developer estimated these costs to be about $40,000 including labor, equipment, materials, and miscellaneous expenses, such as per diem rates, travel costs, and personal protective equipment. As discussed earlier, no provision for a leachate collection, storage, and treatment system was included for either plot.

Utility connection costs for electricity and water have been included even though some sites may not require these. A minimum of 110 V electric service was assumed to be required for the office trailer (lights, air conditioning, heater, outlets, etc.). For the ex situ case, additional power will be required to run small blowers that separate the two sheets of polyethylene in the greenhouse canopy. Water is necessary for irrigation, decontamination, and hygiene purposes. An additional $7,500 has been included for an irrigation system in the ex situ plot greenhouses. The *in situ* plot relied on natural precipitation for irrigation due, in part, to lower contaminant concentrations. Irrigation equipment may also be installed for the *in situ* plot but this cost has been included here.

Trailer rentals have been included even though some sites may not require them. Costs were linearly scaled up according to treatment time, and rates were obtained from this and other SITE projects. For the ex situ case, it may be cheaper to purchase the trailers and amortize their costs over the 5-year life of the project rather than rent them. Also, additional portable toilets and perhaps a septic tank hookup would be required in those instances where additional people would be onsite, i.e., between treatment cycles.

Although security fencing may already exist on some sites, the cost for additional fencing to separate the treatment area from other operations at the site was included. The cost ($4/linear ft) was obtained from previous SITE demonstrations. The length of fencing required for each plot was obtained by assuming a square geometry and finding the length of a side by taking the square root of the plot area. This was multiplied by 4 to get the perimeter and multiplied again by 3 to account for additional space that may be required for support structures or for maneuvering equipment around the site.

The cost to buy and install two 9 m (30 ft) wide and 230 m (760 ft) long greenhouses was obtained from GRACE

Table 3-1. Estimated Full-Scale Remediation Costs using the GRACE Bioremediation Technologies DARAMEND™ Treatment Technology for Two Cases

Cost Category	In situ Plot 6,800 m^3 (11,400 m^2)		Ex situ Plot 1,360 m^3 (2,300 m^2)	
	$	%	$	%
1. Site preparation				
Treatment Plot Fabrication	45,000		55,000	
Utility Connections	2,250		9,750	
Trailer Rentals	6,550		30,400	
Fence Installation	16,800		7,500	
Greenhouse Construction			70,000'	
Total Costs	70,600	11.4	172,650	18.0
2. Permitting and Regulatory Requirements	$3,000	0.5	$3,000	0.3
3. Capital Equipment	9,600	1.5	8,500	0.9
4. Startup				
Soil Preparation	23,500		4,700	
Amendment Incorporation	116,000		23,100	
Fixed Costs	960		850	
Total Costs	140,000	22.6	28,700	3.0
5. Consumables and Supplies				
Amendment Incorporation for Successive Treatment Cycles			92,400	
Gasoline	250		250	
Health and Safety Gear	2,000		2,000	
Total Costs	2,250	0.4	94,700	9.9
6. Labor				
Maintaining Treatment	52,000		18,800	
Changeover (soil preparation)	—		260,000	
Total Costs	52,000	8.4	279,000	29.1
7. Utilities	—	—	2,100	0.2
8. Effluent Treatment & Disposal	—	—	—	—
9. Residuals and Waste Shipping & Handling	316,000	51	340,000	35.4
10. Analytical Services	20,000	3.2	20,000	2.1
11. Maintenance and Modifications	—	—	6,000	0.6
12. Demobilization	5,700	0.9	4,600	0.5
Total	619,150	99.9	959,250	100

Table 3-2. Site Preparation Costs

Cost Item	*In situ* Plot 6,800 m^3 (11,400 m^2)	Ex situ Plot 1,360 m^3 (2,300 m^2)
1. Treatment Plot Fabrication		
a. Earth work (cleaning debris and brush, and soil grading)	$45,000	$15,000
b. Preparation of sand buffer zones, fiberpad, and polyethylene liner to house contaminated soil in treatment plot		$40,000
Total	$45,000	$55.000
2. Utility Connections		
a. Electricity (110 V service)	$1,250	$1,250
b. Water	$1,000	$8,500
Total	$2,250	$9,750
3. Trailer Rentals		
a. Office trailer (12' x 60' w/ 4 office rooms and toilet) - $400/mo	$4,800	$24,000
b. Portable toilet and septic tank - $300/mo.	3 mo.	7 mo.
	$900	$2,100
c. Garbage dumpster (6 cu. yd.) - $70.50/mo.	$850	$4,250
Total	$6,550	$30,400
4. Installation of Fence ($4/linear ft)	4,200 linear ft.	1,900 linear ft.
Total	$16,800	$7,500
5. Purchase and Installation of Two Greenhouses (3O'W x 76O'L each)		$70,000
Total SITE Preparation Costs	$70,600	$172,650

Bioremediation Technologies. This included the purchase price as well as the cost to securely anchor the structure to the ground to prevent damage from high winds and the installation of large access doors for heavy earth moving equipment.

3.4.2 Permitting and Regulatory Requirements

This category includes costs associated with system health/safety monitoring and analytical protocol development, as well as permitting costs. Permitting and regulatory costs can vary greatly because they are very site- and waste-specific. For the Domtar Wood Preserving Facility the only environmental permit required was an alteration to the Ontario Ministry of Environment and Energy Certificate of Approval for liquid, solid, and gaseous waste handling.

For the greenhouse, a building permit may be required from the local governing body before construction commences. Additional requirements to be considered are flame spread index of the greenhouse material, appropriate number and location of emergency exits, installation of CO monitors and/or smoke detectors, and adoption of proper health and safety procedures while working in the greenhouse, such as the "buddy system."

An estimated $3,000 has been assigned to this cost category to allow for technical support services that GRACE Bioremediation Technologies would provide to the client. The reader should be aware that obtaining and complying with permits and any other applicable regulatory standards could potentially be a very expensive and time-consuming activity.

3.4.3 Capital Equipment

Bioremediation technologies are inherently not capital equipment intensive. Since the heavy earth moving equipment is necessary for a relatively short period of time, it is far more economical to contract out those services than it is to tie up capital in purchases.

Therefore, for purposes of this analysis, it has been assumed that OSHA-trained personnel and any necessary equipment would be contracted during startup and demobilization, to set up the treatment plot and subsequently decommission it. For the ex situ plot, the intermediate process of replacing treated soils with contaminated soils for each treatment cycle was also assumed to be done by contracted personnel and has been included in the Labor cost category.

The only piece of hardware required to successfully implement this technology is a tractor to run the rototiller. The cost of purchasing vs. renting would be dependent on the size of the plot and the treatment time. The cost to rent was assumed to be $800/mo while the purchase price was estimated to be $17,000. For a 12 month period, it is advantageous to rent at a yearly cost of $800/mo x 12 mo = $9,600 rather than buy. Conversely, for the ex situ plot, buying the tractor and amortizing the cost over a useful life of 10 years yields an annual expense of $1,700, or $8,500 for the 5-year duration of the remediation.

GRACE Bioremediation Technologies considers the rototiller to be a commercially proprietary item and an integral part of its treatment process. Its cost has been included as part of amendment addition under the startup category on a $/m³ basis.

3.4.4 Startup

Startup activities for this technology include excavating, screening, handling the oversized material, adding the amendment, and homogenizing the soil. As discussed under Capital Equipment costs, it was assumed that some of these activities would be contracted out for both of the cases considered.

The work was divided into two segments. In preparation for amendment addition, the first segment involved excavating, screening, and handling the oversized material. For the *in situ* case, this was primarily accomplished by a subsurface ripper and rock picker. For the ex situ plot, the soil was excavated, screened through a 10 cm (4 in.) grizzly screen and deposited onto the treatment plot. All of these tasks were assumed to be contracted out. Based on experience, GRACE Bioremediation Technologies estimated that soil could be processed at a rate of approximately 14.5 m^3/hr (19 yd^3/hr). The LE&M rate was inferred from the SITE demonstration to be $50/hr, including all necessary equipment and materials. The reader is cautioned that this hourly rate can vary greatly according to geographic location and should be conservatively estimated for the site under consideration.

The second segment involved adding the amendment and homogenizing the soil using the rototiller to ensure uniform treatment. These tasks were assumed to be handled by GRACE Bioremediation Technologies personnel. Amendment type and dosage are very site-specific. Key factors that affect these parameters are contaminant type and concentration, and physical characteristics and nutrient content of the soil. The amendment may be added all at once or periodically throughout treatment, depending on soil properties and the extent of remediation. For the sake of simplicity, it was assumed that the necessary amendment was added during Startup and that no further amendment additions were required. The cost of amendment addition would typically include the cost of the amendment; shipping, handling, and storage; and the associated labor, equipment, and consumables necessary to incorporate the amendment into the soil matrix. Based on these factors, a reasonable estimate for amendment addition was given by GRACE Bioremediation technologies as $1 7/m³ of soil.

For the ex situ plot, the cost of soil preparation for successive treatment cycles was considered under the Labor cost category. Similarly, the cost of incorporating the amendment into the soil matrix for successive treatment cycles was included in the Consumables and Supplies cost category.

Fixed costs such as insurance and taxes were assumed to be 10% of annual capital equipment costs or $960 for the *in situ* plot and $850 for the ex *situ* plot.

3.4.5 Consumables and Supplies

The main item that could be considered "consumable" for this process would be the amendment. This may not necessarily be a one-time charge. As discussed under Startup, depending upon how well the remediation is progressing, new amendment may need to be added periodically. For simplicity, it was assumed that amendment was added only at the beginning with no further additions for the remainder of treatment. For the ex situ case, this would have to be repeated for every treatment cycle, and this cost is accounted for as shown in Table 3-l.

Other items that should be included here are the gasoline required by the tractor, and health and safety gear. Gasoline for the tractor was assumed to cost about $5/wk for the *in situ* plot and $1 /wk for the ex *situ* plot. Either way, the total cost of gasoline for the tractor to treat 6,800 m³ of contaminated soil is about $250. Health and safety gear was estimated to cost about $2,000 a year.

3.4.6 Labor

Once the treatment plot is established and amended, the amount of labor involved is minimal. Rototilling to aerate the soil once every two weeks, irrigating as necessary, taking moisture and temperature readings every two weeks, sampling to determine the extent of bioremediation that has occurred, and maintaining the facility and equipment is about all the work that is required. GRACE Bioremediation Technologies has indicated that labor costs are dependent on plot size and intensity of sampling. Based on experience from the SITE demonstration, it was estimated that this would require no more than two people working a standard 40-hour week. An hourly labor rate of $13/hr was assumed; this includes a base salary, benefits, overhead, general and administrative (G & A) expenses, travel, per diem, and rental car costs. This would yield a labor cost of $52,000 annually.

The largest contributor, however, is the work associated with multiple treatment cycles. As discussed under Startup costs, the total LE&M for additional treatment cycles for the ex *situ* plot is $260,000, while plot maintenance is estimated to cost only $18,800.

3.4.7 Utilities

The major utility demand for this project was electricity. In addition to the power required for the office trailer, electricity was used to power the blowers separating the two layers of polyethylene sheeting on each greenhouse for the ex *situ* plot. The blowers were required every 45 m (150 ft) and were rated at 1.15 amps at 115 V (133 watts). Therefore, six blowers for the two greenhouses were required for a total of 800 watts. At $0.06/kWh, the electricity usage for the ex *situ* plot would be $420/yr (0.8 kW x 24 hr/day x 365 days/yr x $0.06kWh) or about $2,100 for the 5 year period.

The primary use of water for the ex situ plot was irrigation. The irrigation demand is dependent on season, soil character, treatment protocol, temperature, and climate. The in situ plot relied solely on natural precipitation. The cost of water usage for the ex situ plot was estimated to be so low that no value was assigned.

3.4.8 Effluent Treatment and Disposal

Since there was no leachate produced during the SITE demonstration of the ex situ plot, it was assumed that no leachate would be produced during the course of the full-scale remediation. Pilot-scale testing showed that this would also.be true for the in situ plot. Therefore, there were no costs assigned to this category for either case.

3.4.9 Residuals and Waste Shipping, Handling, and Storage

During the SITE demonstration, oversized material separated out during the Startup phase was analyzed and found to be hazardous. Because this may not necessarily be the case at every site, residual disposal costs were estimated two ways. First, it was assumed that the residual was a hazardous waste and needed to be handled appropriately offsite. Secondly, it was assumed that it was not hazardous and could be landfilled at the same site with no additional costs incurred.

The oversize material was 7% by volume of the total soil treated. The average bulk density was assumed to be 1.3 tons/m^3 or about 620 tons for the 6,800 m^3 of soil. The cost of landfilling hazardous material was assumed to be $5001 ton. It should be pointed out that landfilling PCP contaminated waste may not be permissible in some jurisdictions. In that case, the only disposal option would be incineration at 2 to 3 times the cost of landfilling. Therefore, if this material is hazardous, disposal costs may be as low as $300,000 or as high as $1 ,OOO,OOO.

The only other residual generated during the course of the SITE demonstration that required disposal was PPE. This cost would probably be greatest during site preparation, startup, and demobilization activities, and between treatment cycles for the ex situ plot. PPE usage should be minimal during treatment. It was assumed that an average of one drum of PPE per month of treatment would be generated. At a disposal cost of $500/drum, this would translate to $6,000 for 12 months of treatment.

3.4.10 Analytical Services

The project analytical costs will necessarily be dependent on site-specific factors, such as regulatory requirements regarding sampling intensity, frequency, and analyses. For this estimate, a sampling program that generates one sample per 100 m^3 was assumed. Thus, 68 samples per sampling event would be generated for 6,800 m^3 of soil. Soil moisture, temperature, and pH would be measured every two weeks at an internal cost of $10. This would then total $16,320 (68 samples/event x 2 events/ month x 12 months x $l0/sample). To determine the progress of treatment, PCP and PAHs would be measured less frequently, perhaps once every quarter. To account for the costs of PAH/PCP analyses, duplicate samples, additional samples/analyses required by regulatory agencies, and shipping and handling, this category was estimated at $20,000.

3.4.11 Facility Modification, Repair, and Replacement

Replacement, repair, and/or modification of the sand layers, polyethylene liner, and/or the fiberpad in between treatment cycles may be necessary. This has been estimated at $1,500 per treatment cycle or $6,000 for four treatment cycles. Seasonal modifications to the greenhouse, such as opening the side vents at the beginning of the summer season and closing them at the beginning of the winter season, are considered negligible costs and therefore have not been included.

3.4.12 Demobilization

Demobilization of the in situ plot would require minimal effort. The key tasks would be levelling, seeding, and compacting the treated area. The cost is estimated to be about $5,700.

For the ex situ area, the demobilization would involve dismantling the greenhouse, removing the synthetic treatment pad material, returning treatment pad soil and clay to the site as clean fill, levelling, seeding, and compacting the treatment area. It is estimated that the cost of these activities would be about $4,600.

3.5 Results

The results indicate that a full-scale cleanup of this site using this technology would cost between $619,000 and $959,000, including the cost of residual disposal. The corresponding unit costs would range from $92/$m^3$ ($70/$yd^3$) for the in *situ* plot to $1 40/$m^3$ ($1 08/$yd^3$) for the ex situ plot. Without residual disposal, the unit costs decrease substantially; $46/$m^3$ ($35/$yd^3$) for the in situ plot, representing a 50% reduction, and $96/$m^3$ ($73/$yd^3$) for the ex situ plot, representing a more modest but still significant 31% reduction. In either case, the in *situ* plot was far more economical to setup and operate than the ex *situ* plot (it would cost 34% less with residual disposal, and 52% less without residual disposal).

Although this is a considerable difference, there could be circumstances where ex *situ* treatment would be more advantageous than *in situ* treatment. For instance, recalcitrant soils with high contaminant concentrations could be treated in an ex *situ* greenhouse, which allows better control over moisture content and temperature and, therefore, more uniform treatment without isolated pockets of high concentration soils. For the same initial contaminant concentration, treatment in the controlled environment of a greenhouse would be faster than relying solely on natural irrigation and temperatures. Finally, ex situ treatment in a greenhouse may be more easily accepted by the community than uncovered *in* situ treatment, even though there might not be a technical advantage.

The 12 cost categories for the two cases considered here are shown in Figure 3-l. Figure 3-2 displays the same cost categories minus the cost category Residuals + Waste Shipping + Handling. For both the *in situ* and ex situ plots, the predominant cost category was Residuals & Waste Shipping & Handling (51% for the *in situ* case vs. 35% for the ex situ case).

For the *in situ* plot, the next highest cost categories were Startup (22%), Site Preparation (11%) and Labor (8%). These four highest cost categories accounted for over 90% of total costs. Analytical Services (3%), Capital Equipment (2%) and Demobilization (1%) were the next largest contributing factors. Permitting and Regulatory Requirements and Consumables & Supplies each contributed 0.5% or less to total costs.

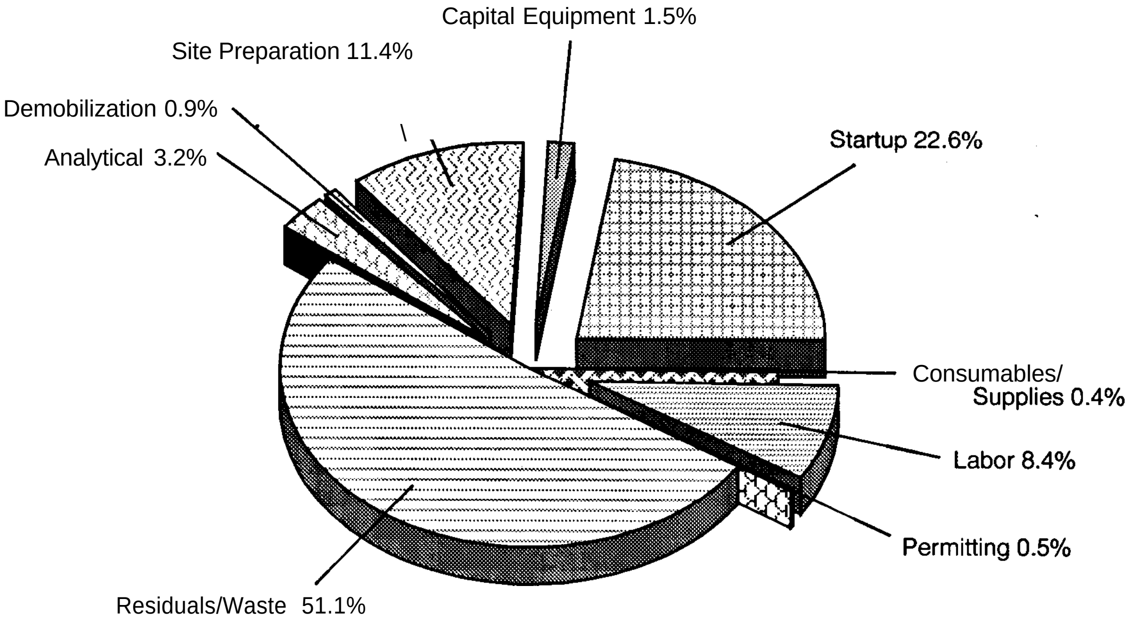
For the ex *situ* plot, the Residuals & Waste Shipping & Handling cost category was followed by Labor (29%), Site Preparation (18%), and Consumables & Supplies (10%). These four items again accounted for over 90% of costs. Startup (3%), Analytical Services (2%), and Capital Equipment (1%) were the next largest categories. Maintenance and Modifications and Demobilization each contributed about 0.5%, while Permitting and Regulatory Requirements and Utilities were insignificant cost contributors.

No costs were attributed to Effluent Treatment and Disposal for either plot because it was assumed that no leachate would be generated. This observation was confirmed during the SITE demonstration project on the ex situ plot.

For both plots, Labor and Site Preparation were among the top four cost categories. In the case of the ex situ plot, this is related to the construction of the treatment pad, the purchase and installation of the greenhouse, the additional labor connected with multiple treatment cycles, and the accompanying longer treatment times associated with a smaller plot. For the *in situ* plot, these costs are a reflection of the larger plot size assumed. Cost contributions from Analytical Services, Capital Equipment, Demobilization, and Permitting and Regulatory Requirements are about the same for both plots. This indicates that these categories are not dependent on the size of the site. Maintenance and Modification and Utility costs were insignificant for the *in situ* plot because of the relatively short cleanup time involved.

This section presents the results of the EPA SITE demonstration conducted at the Domtar Wood Preserving Facility in Trenton, Ontario, Canada. This section discusses the effectiveness of the DARAMEND™ Bioremediation Technology in remediating PAHs and CPs in wood treatment soils.

In Situ Plot (6800 m^3)



Ex Situ Plot (1360 m^3)

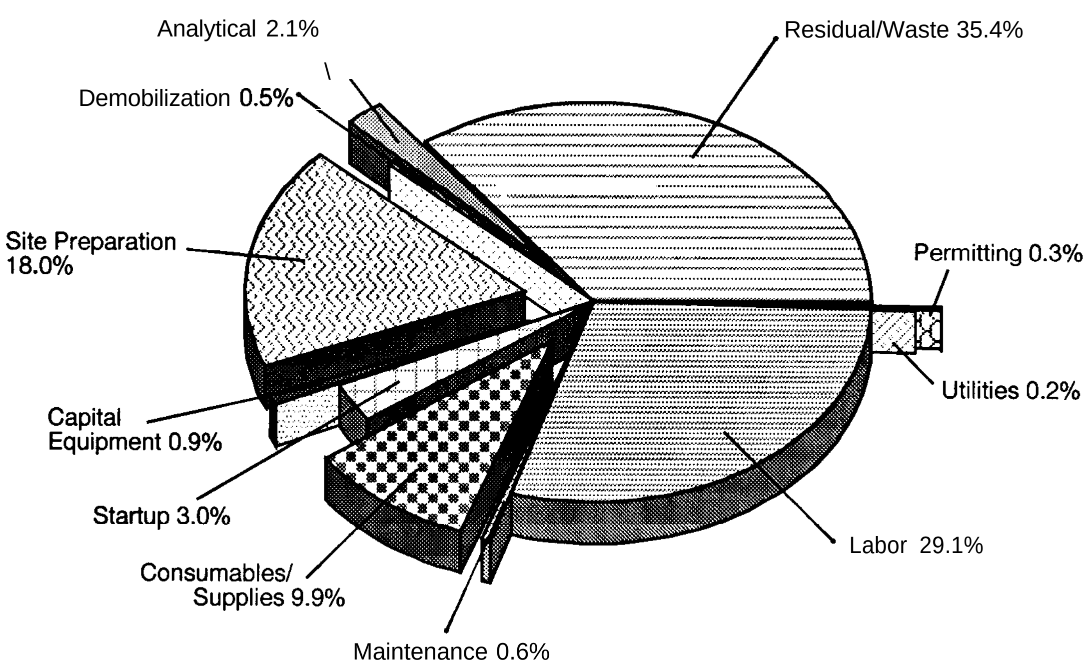
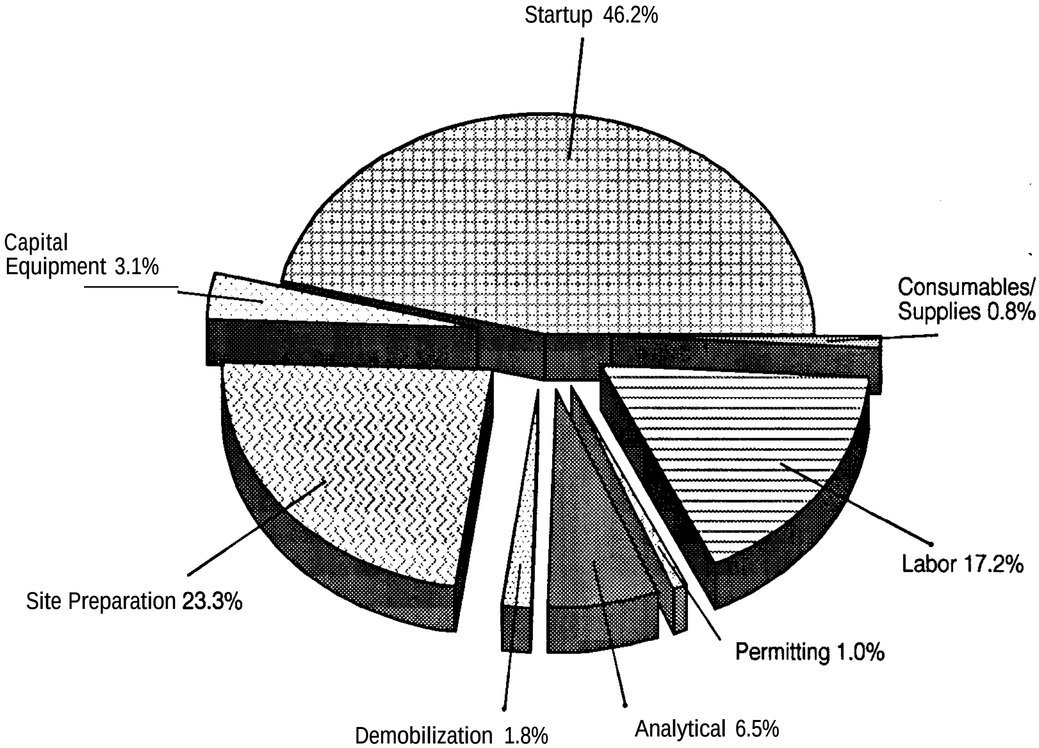


Figure 3-1. Estimated full-scale remediation costs.

In Situ Plot (6800 m^3)



Ex Situ Plot (1360 m^3)

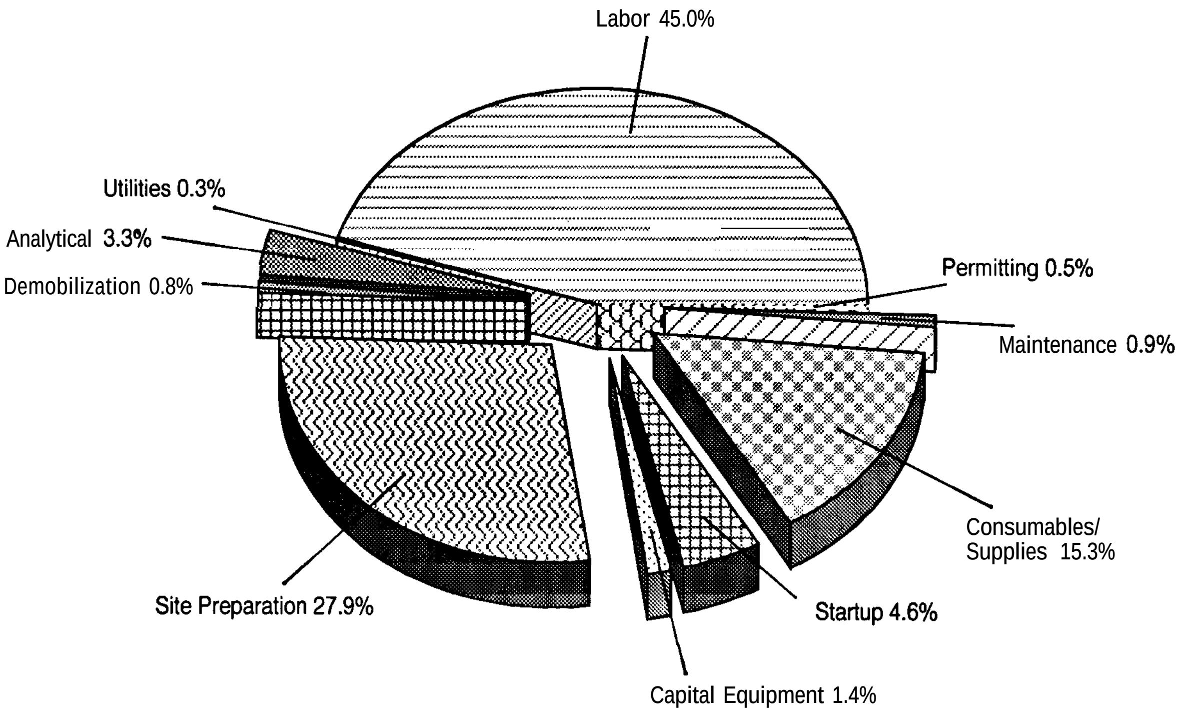


Figure 3-2. Estimated full-scale remediation costs.

Section 4
Treatment Effectiveness

4.1 Background

The DARAMEND™ Bioremediation Technology SITE demonstration utilized a portion of a much larger full-scale demonstration area being treated simultaneously by GRACE Bioremediation Technologies, the developer, at the Domtar site. The full-scale technology demonstration was co-funded by Domtar, Environmental Canada, and the Ontario Ministry of the Environment. GRACE Bioremediation Technologies, was contracted to treat 3,000 tons of soil *in situ* and 1,500 tons of excavated soil (ex *situ)* at the Domtar site, for a period of approximately one year. The SITE demonstration involved the treatment of approximately 300 tons of excavated soil. GRACE Bioremediation Technologies installed, maintained (i.e., tilling and irrigation), and monitored the ex *situ* treatment system, which covered an area of approximately 2,300 m^3. The EPA SITE demonstration involved the construction of a separate Treatment Plot and No-Treatment Plot that were monitored and maintained by the developer.

The Domtar Wood Preserving Facility operated for several decades at the site and was responsible for the deposition of CPs, creosote, and petroleum hydrocarbons to the native soil. The wood preserving process has been discontinued at the facility and the property is currently used for the storage of treated lumber, railroad ties, and telephone poles. In the past decade, soils surrounding the former process area have been excavated and stockpiled for treatment. The SITE demonstration focused on these soils which, according to the developer, have the highest concentrations of PAHs and CPs. Historical data collected by the developer indicated that the excavated soil contains total chlorophenol concentrations from 276 mg/kg to 1228 mg/kg (PCPI from 249 mg/kg to 1176 mg/kg) and total PAHs from 577 mg/kg to 2068 mg/kg.

Prior to the SITE demonstration, EPA collected composite samples of the soil to be used in the Treatment and No-Treatment Plots. The Treatment Plot exhibited total PAH concentrations ranging from 2274 mg/kg to 3453 mg/kg and total chlorinated phenol concentrations ranging from 540 mg/kg to 740 mg/kg (only PCP was detected). The No-Treatment Plot exhibited a total PAH concentration of 1718 mg/kg and a total chlorinated phenol concentration of 360 mg/kg (only pentachlorophenol was detected).

This SITE demonstration was conducted to evaluate the performance of GRACE Bioremediation Technologies' DARAMEND™ Bioremediation Technology to remediate PAH and chlorinated phenol contamination in soils from the Domtar Wood Preserving Facility in Trenton, Ontario. According to the developer, the DARAMEND™ Technology is an effective bioremediation alternative for the treatment of soils containing levels of CPs and PAHs typically considered too toxic for bioremediation.

The developer claimed that the DARAMEND™ Bioremediation Technology can achieve a 95% reduction in total PAHs and a 95% reduction in TCP over an eight-month period of treatment. The performance was evaluated using the pre- and post-treatment concentrations of the analytes listed below:

Total PAHs

- Naphthalene
- Acenaphthalene
- Acenaphthene
- Fluorene
- Phenanthrene
- Anthracene
- Benzo(g,h,i)Perylene
- Fluoranthene
- Pyrene
- Chrysene
- Benzo(a)pyrene
- Benzo(b)fluoranthene
- Benzo(k)fluoranthene
- Benzo(a)anthracene
- Indeno(l,2,3-c,d)pyrene
- Dibenzo (a,h)anthracene
- Benzo (g,h,i) perylene

Total Chlorinated phenols

- 2-chlorophenol
- 2,4-dichlorophenol
- 2,4,5-trichlorophenol
- 2,4,6-trichlorophenol
- Pentachlorophenol

The total list of CPs presented by the developer has been abbreviated to the above list, which includes only those analytes routinely analyzed under SW846 3540/8270. Data collected during the developer's pilot testing program have shown that PCP comprises 96% of the total contamination contributed by This being the case, the elimination of chlorinated phenolic compounds not routinely analyzed in

SW3540/8270 had a negligible effect on the measured performance of this technology.

As the process is temperature-dependent, the treatment period only includes days when the average daily soil temperature within the greenhouse was above 15°C. The demonstration was originallv scheduled to run until the beginning of June 1994: but was extended by the 93 days that the greenhouse average soil temperature fell below 15°C. The actual number of treatment days between the initial baseline sampling and the final sampling event totaled 254. A summary of sampling and data monitoring activities is presented in Figure 4-l.

Primary (Critical) Project Objectives

The SITE demonstration was designed to determine whether the developer's claim could be achieved during a full-scale application of the technology. The primary objective was evaluated by comparing the sums of the concentrations of select PAHs and CPs in soils within the demonstration Test Plot, after 254 days of treatment by the DARAMEND™ Bioremediation Technology. The Test Plot was physically separated from the GRACE Bioremediation Technologies plot and was evenly divided into 54 2 x 2 meter subplots. Soil samples for critical analyses were collected from designated subplots using a random number generator as discussed in the TER. Homogenized soil cores from each of the designated subplots were analyzed for SVOCs using analytical SW846 Method 3540/8270.

Secondary (Non-Critical) Project Objectives

Other objectives of the demonstration included:

- Determine the magnitude of reduction in the sums of the concentrations of select PAHs and CPs in the No-Treatment Plot soils.
- Determine the magnitude of reduction for specific PAHs and chlorinated phenolic compounds within each of the SITE demonstration plots.
- Determine the toxicity of the soil to earthworms and seed germination in each of the SITE demonstration plots before and after treatment.
- Monitor the fate of TRPH in each of the SITE demonstration plots.
- Monitor general soil conditions (i.e., nutrients, toxins) that might inhibit or promote process effectiveness, such as TC, TIC, Nitrate-Nitrite, Phosphate, TKN, pH, PSD, Chlorides and Total Metals within each of the SITE demonstration plots.

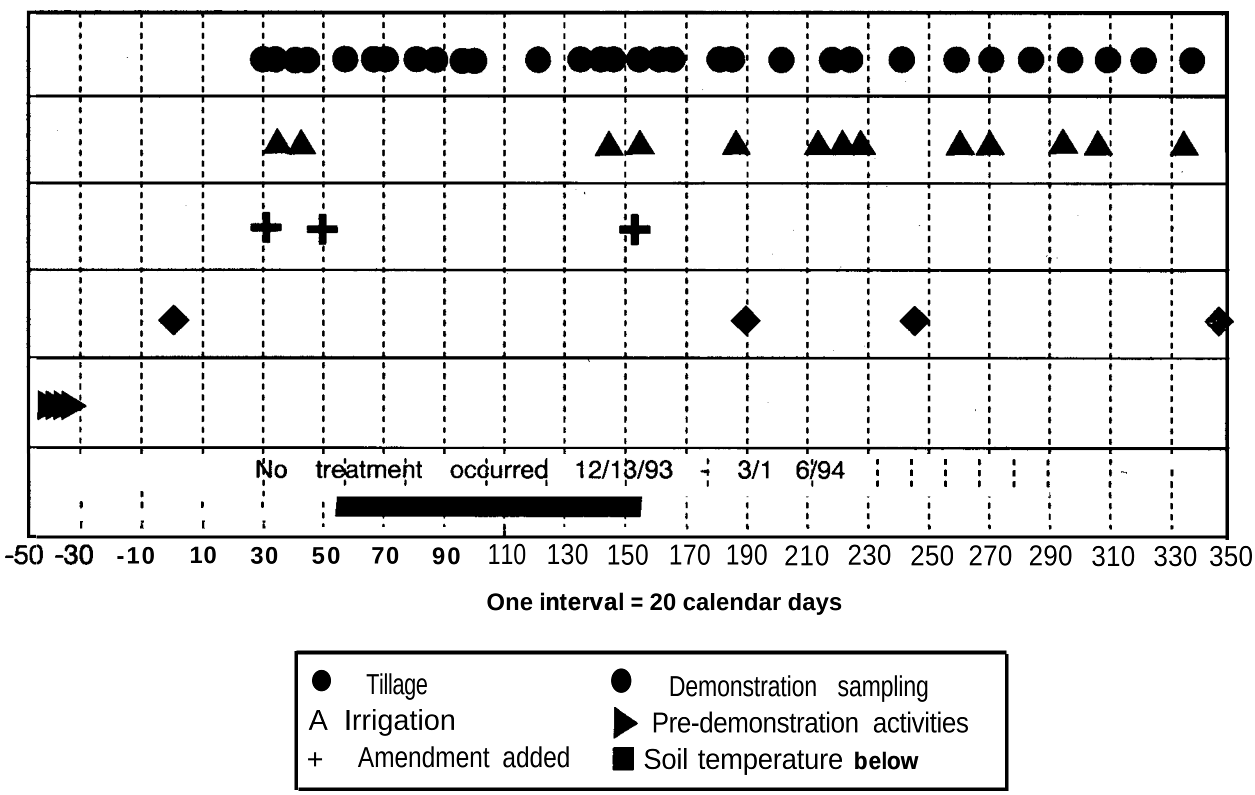


Figure 4-1. Maintenance Record.

- Monitor for the presence of leachate within the SITE demonstration Test Plot.

- Monitor each of the SITE demonstration plots for active microbial populations, specifically focusing on total heterotrophs and PCP degraders, as a way to qualitatively assess the magnitude of biodegradation over the course of the eight-month test.

- Monitor the upper sand layer in contact with the treated soil to qualitatively assess any tendency for downward migration of contaminants.

These primary and secondary project objectives were evaluated through a carefully planned and executed sampling and analysis plan (see TER). For this demonstration SVOCs were considered critical during "Baseline" and "Post-Treatment" sampling (Event #0 and Event #3) of the SITE demonstration Treatment Plot. This parameter was considered noncritical during sampling of the No-Treatment Plot and during the two intermediate rounds of Treatment Plot sampling (Event #l and Event #2). The period of performance evaluation was estimated by the developer to be approximately 240 days (actual 254 days) starting on October 14, 1993 (Event #0) and ending on September 26, 1994 (Event #3). The two intermediate rounds were performed on the 88th day and on the 144th day of treatment which occurred on April 21, 1994 and on June 14,1994 (Events #l and #2). No sampling was conducted during the winter months of December, January, February, and March since little biodegradation was expected to occur at low winter temperatures.

An additional objective of this demonstration was to develop data on operating costs for the DARAMEND™ Bioremediation Technology so that the applicability and cost effectiveness of this process at other sites could be evaluated. The results of the economic analysis were presented in Section 3.

4.2 Detailed Process Description

GRACE Bioremediation Technologies demonstrated their patented DARAMEND™ Bioremediation Technology on a portion of an ex situ plot located in a 10 x 200 m greenhouse-enclosed treatment plots installed along the northwest corner of the Domtar Wood Preserving Facility. The SITE plots consisted of a 2 x 6 m No-Treatment Plot and a 6 x 36 m Treatment Plot. Both plots were constructed and bermed off from the larger GRACE Bioremediation Technologies plot to facilitate testing under the SITE Program. The Treatment Plot underwent treatment by the DARAMEND™ Bioremediation Technology and was maintained in the same manner as the larger GRACE Bioremediation Technologiesplot. The No-Treatment Plot received no treatment and was left idle and covered throughout the demonstration period.

The excavated soil provided for the SITE demonstration plots, according to the developer, had a total chlorophenol concentration in the range of 276 mg/kg to 1228 mg/kg (PCP from 249 mg/kg to 1 ,176 mg/kg); total PAHs ranged from 557 mg/kg to 2068 mg/kg. Actual Test and No-Treatment Plot concentrations were verified during the pre-demonstration sampling effort conducted a month before the start of the demonstration (September 7, 1993). Prior to placing the test soil in the SITE demonstration plots, the test soil was screened by the developer to remove debris that might interfere with the homogenization or incorporation of organic amendments (see Sections 4.4.1 and 4.4.4 regarding the soil screening process). The screened soil was transported to the treatment area and stockpiled on a polyethylene liner until construction of the SITE demonstration plots was complete.

The No-Treatment Plot was physically isolated from the adjacent treatment areas by wooden walls that rose 1.5 m above the surface of the soil, extended downward through the soil and the underlying sand layer, and rested on the fiberpad that protected the underlying plastic liner. This was done to protect the No-Treatment Plot soil from inadvertent inoculation by nearby tillage or by the migration of subsurface water.

GRACE Bioremediation Technologies treated the soil in the SITE demonstration Treatment Plot through the addition and even distribution of its solid-phase organic amendments using a specially designed rotary tiller. Tilling serves the dual purpose of reducing variations in soil physical and chemical properties and aerating the soils. The developer determined the WHC of the Treatment Plot soils and employed a specialized soil moisture control system to encourage the proliferation of large active microbial populations and limit the generation of leachate. These are considered proprietary components of the developer's process. Figure 4-l illustrates the overall schedule of the demonstration, depicting the number of calendar days on which sampling, tillage, irrigation, and the addition of amendments occurred. In addition, Figure 4-1 depicts a total of 93 "no treatment days," from December 13, 1993 to March 16, 1994, when the soil temperature in the Treatment Plot was below 15°C.

Plot Construction

The Treatment and No-Treatment Plots were contained at the northern end of a temporary "greenhouse" that also housed GRACE Bioremediation Technologies' demonstration plot (See Figure l-2). The waterproof structure consisted of an aluminum frame covered by a shell of polyethylene sheeting and could be opened at each end to allow for equipment access.

Both the Treatment and No-Treatment Plots were underlain with a high-density polyethylene liner (impermeable to the target compounds). This liner was underlain with 10 cm of screened sand to prevent structural damage to the liner. Another 15-cm-thick sand layer and a 4-mm-thick fiberpad were spread on top of the liner to minimize the potential for direct contact between the liner material and tillage equipment.

Once the upper bedding material had been spread across the plot, the targeted test soil was screened and then deposited within the lined plots to a depth of 0.6 m. Each demonstration plot was isolated from the adjacent plots by earthen berms with wooden boards protruding 1.5 m above the top of the soil. One side of the Treatment Plot remained open for tilling equipment access.

Decontamination Pad

GRACE Bioremediation Technologies constructed a decontamination pad adjacent to the demonstration area to facilitate cleaning of the tilling equipment and prevent cross-plot contamination.

Site Preparation for Treatment

Soil targeted for treatment by the DARAMEND™ Bioremediation Technology was prepared by GRACE Bioremediation Technologies prior to being placed in the control and treatment plots. Soil stored near the wood treatment site was collected with a backhoe and introduced into a screening device in order to remove debris (rocks, wood, metal) that could interfere with incorporation of the organic amendment. Oversized debris was stockpiled in a secure area near the runoff collection and treatment area, to prevent the generation of leachate containing the target compounds. Screened soil was then transported to the treatment area and spread onto the prepared No-Treatment and Treatment Plots to a depth of 0.5 m.

The soil matrix was initially homogenized in both the Treatment and No-Treatment Plots by tilling with a power take-off driven rotary tiller to ensure uniform physical and chemical soil properties, and to facilitate distribution of soil amendments. GRACE Bioremediation Technologies utilized two tillers, each of which was pulled by a 75 hp tractor. The tillers are 2.1 and 1.7 m wide and can reach an effective depth of 60 cm.

After homogenization GRACE Bioremediation Technologies' patented amendment was added to the Treatment Plot soil in a volume of approximately 1% of the total volume of the soil. The organic amendments increase the supply of biologically available water and nutrients to contaminant-degrading microorganisms. Addition of the amendments may increase the soil volume up to 15% depending on the amount of pore space present. Typically amendments are added solely at the beginning of the treatment process, however, an additional 2% was added in December 1993, and an additional 1% was added in March 1994, based on soil sample analytical results.

Plot Maintenance

Figure 4-1 illustrates the frequency of Treatment Plot maintenance, which consisted of the following tasks:

- tilling the plot using a tractor and tiller
- monitoring for moisture and temperature
- irrigating the plot

Soil in the Treatment Plot was tilled immediately after the commencement of irrigation, and at weekly intervals thereafter, to increase diffusion of oxygen to microsites and to ensure the uniform distribution of irrigation water in the soil profile.

All plot monitoring was performed by the developer, and a daily log of measurements was maintained. The frequency of irrigation was determined by weekly monitoring of soil moisture conditions; successful bioremediation depends on maintenance of the soil's water holding capacity. The growth rate of microbial biomass was characterized via regular monitoring of soil temperature using a commercial version of a hand-held thermocouple.

4.3 Methodology

4.3.1 *Sampling*

Pre-Demonstration

During the week of September 7, 1993, representative soil samples were collected by the SITE contractor from both demonstration plots to satisfy the following pre-demonstration objectives:

- Characterize the target media for treatment
- Ensure the presence and concentration of target compounds present in the target media
- Identify any conditions present in the soil that could inhibit the treatment process or its validation.

The pre-demonstration sampling plan called for five composite samples to be collected using hand augers; however, the soil contained large stones and concrete debris that necessitated the use of a pick-axe and shovel. All samples were analyzed for SVOCs (which included PAHs and CPs) and one composite was analyzed for metals, VOCs, pesticides/PCB's, PSD, and dioxins/furans. One composite sample from the No-Treatment Plot was collected and analyzed for SVOCs, metals, VOCs, and PSD. Due to the amount of oversized material (greater than l/2-inch), three composite samples were screened in the field using a l/2-inch screen to determine the ratio of rocks to soil in the plots. In addition, a representative sample of the undersized and oversized soil was collected from each of these three composites and sent to the laboratory for semi-volatile organic analysis (SW 846-8270).

Demonstration

The primary objective of the SITE demonstration was to evaluate the effectiveness of the DARAMEND™ Bioremediation Technology in degrading PAH and CPs contamination in wood-treatment soil at the Domtar site. The collection of soil samples from the Treatment Plot began following pretreatment of the soil, which entailed:

- Screening of the soil to a diameter of 10 cm
- Addition of proprietary organic amendments to the soil (1% of volume of soil)
- Homogenization of the soil and amendments

The 2 m x 6 m No-Treatment Plot received the same screened and homogenized soil as the Treatment Plot but no organic amendments or moisture were added, and no tillage occurred.

The SITE demonstration called for four sampling events These four sampling events were as follows:

Event #0	Baseline	October 14, 1993*
Event #l	Intermediate -	April 21, 1994
Event #2	Intermediate -	June 14, 1994
Event #3	Final	September 26, 1994

Note: * - The day after the amendments were tilled into the soil.

These sampling events in relation to the treatment process are depicted in Figure 4-l. Figures 4-2 and 4-3 show the locations sampled and parameters analyzed within each grid during the four sampling events.

During all four sampling events, grab soil samples were collected from the selected subplots using a hand auger, and were analyzed for SVOCs (SW 846 3540/8270) (which includes the analysis for CPs and PAHs). Portions of soil from each of the subplots were retained and mixed together to form a single composite sample, which was analyzed for the parameters indicated in Figure 4 2 and Figure 4-3.

4.3.2 Data Analysis

The analytical results, once validated, were reduced to develop the average sums of the concentrations of total PAHs, individual PAHs, TCP, and individual CPs. To evaluate the primary objectives, only the initial and final levels of the specified 16 PAHs and the specified 5 CPs (CP) were utilized to calculate the magnitude of reduction of PAHs and CPs in the SITE demonstration Plots.

The total PAH and total CP percent reductions in the SITE demonstration plots were calculated using Equations 1 and 2, respectively:

$$\%\ Red_{PAH} = \frac{\overline{C}_{iPAH} - \overline{C}_{fPAH}}{\overline{C}_{iPAH}} \times (100) = 1 - \frac{\overline{C}_{fPAH}}{\overline{C}_{iPAH}} \times (100) \qquad (1)$$

$$\%\ Red_{cp} = \frac{\overline{C}_{iCP} - \overline{C}_{fCP}}{\overline{C}_{iCP}} \times (100) = 1 - \frac{\overline{C}_{fCP}}{\overline{C}_{iCP}} \times (100) \qquad (2)$$

where,

$\overline{C}_{iPAH}$ = average initial PAH concentration in the plot
$\overline{C}_{fPAH}$ = average final PAH concentration in the plot
$\overline{C}_{iCP}$ = average initial chlorinated phenol concentration in the plot
$\overline{C}_{fCP}$ = average final chlorinated phehol concentration in the plot

The percent reduction of specific compounds in each plot is given by equation 3.

$$\%\ Red_{y} = \frac{\overline{C}_{iy} - \overline{C}_{fy}}{\overline{C}_{iy}} \times (100) = 1 - \frac{\overline{C}_{fy}}{\overline{C}_{iy}} \times (100) \qquad (3)$$

where,

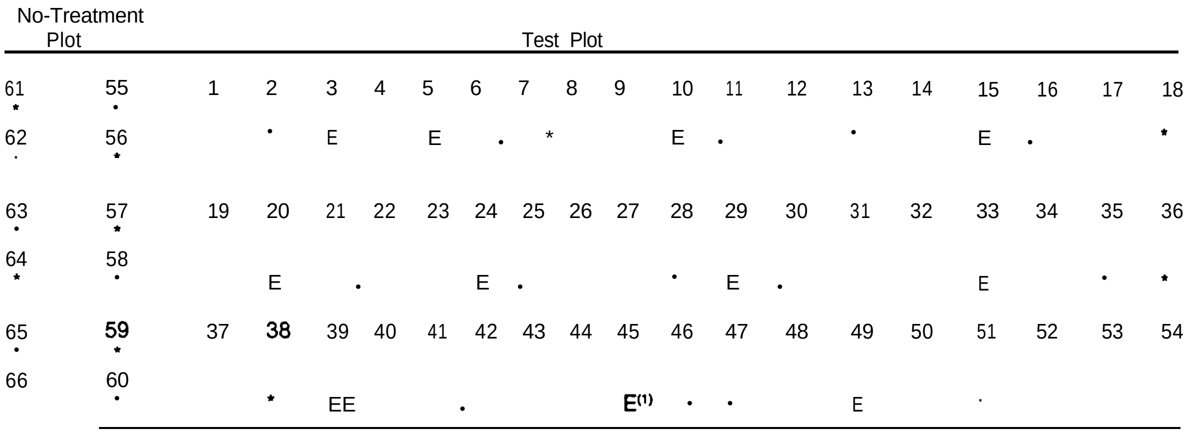
$\overline{C}_{iy}$ = average initial concentration of compound y in the plot
$\overline{C}_{fy}$ = average final concentration of compound y in the plot

In addition, the composite soil data from each plot was evaluated to measure changes in soil toxicity, reduction of TRPHs, concentrations of metals, conventional soil chemistry, and PSD. Separate individual grab samples were also collected and evaluated to track changes in the microbial populations of each plot. Furthermore, the area underlying the demonstration soil was sampled and monitored during each sampling event, for the possible migration of contaminants downward into the underlying sand layer or the presence of leachate collecting on the liner.

4.3.3 Statistical Analysis

The pre-and post-treatment concentration data for total and individual PAHs, and total and individual chlorophenols were used to further compute the point estimates and their respective confidence intervals for removal efficiencies of these contaminants. The basic statistical methodology used toanalyze the data collected during sampling events 0 and 3 is described below. Cls were constructed at two levels of confidence, 80% and 90%.

First the separate pretreatment and post-treatment data were analyzed by constituent in tests of normality on the raw data and tests of log normality on the log-transformed data. These tests indicated that the separate data sets, as wells as the paired ratios of effluent to influent data, gen-

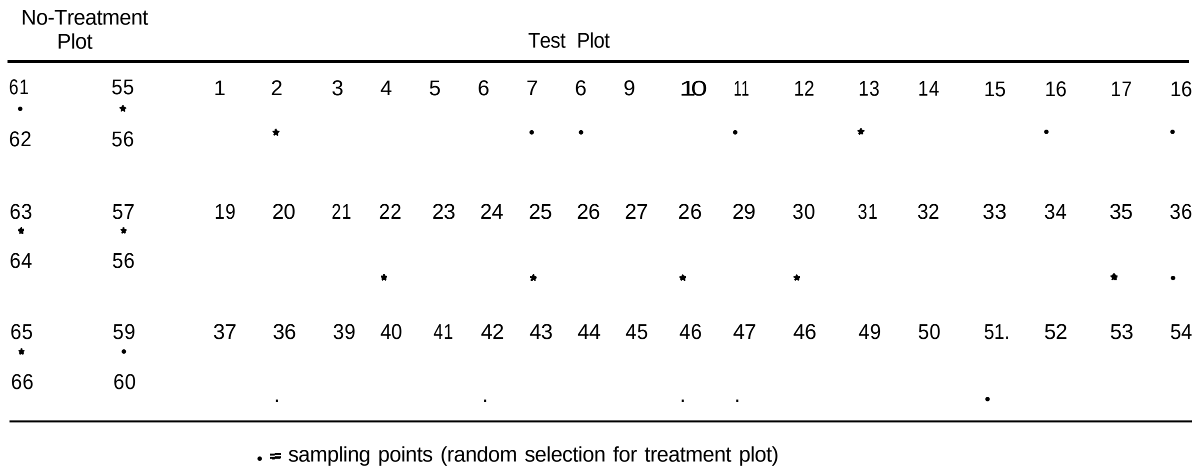


. = sampling points (random selection for treatment plot)

Parameter	Test Plot																		No-Treatment Plot											
	2	7	8	11	13	16	18	22	25	28	30	35	36	38	42	46	47	51	55	56	57	58	59	60	61	62	63	64	65	66
Semivolatiles	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Semivolatiles (Triplicate) MS/MSD		X											X								X									
Semivolatiles - sand			X		X				X																					
Total heterotrophs/ PCP degraders	X		X		X		X		X		X		X		X		X		X		X		X		X		X		X	
Chloride										1 composite														1 composite						
TKN, NO_2/NO_3, PO_4, TC, TIC, pH										1 composite														1 composite						
TRPH										1 composite														1 composite						
Metals										1 composite														1 composite						
PSD										1 composite														1 composite						
Dioxins/Furans										1 composite														—						
Toxicity										1 composite														1 composite						

E - Contingency samples.
E(1) Sampled in triplicate and extracted in the lab as contingency samples (one sample was analyzed for MS/MSD)

Figure 4-2. Soil Sample Aliquots for Sampling Events 0 and 3.



Parameter	Test Plot																		No-Treatment Plot											
	2	7	8	11	13	16	18	22	25	28	30	35	36	38	42	46	47	51	55	56	57	58	59	60	61	62	63	64	65	66
Semivolatiles	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X		X		X		X		X		X	
Semivolatiles (Triplicate) MS/MSD			X											X																
Semivolatiles - sand				X		X				X																				
Total heterotrophs/ PCP degraders	X		X		X		X		X		X		X		X		X		X		X		X		X		X		X	
Chloride										1 composite														1 composite						
TKN, NO_2/NO_3, PO_4, TC, TIC, pH										1 composite														1 composite						

Figure 4-3. Soil Sample Aliquots for Sampling Events 1 and 2.

erally satisfied the assumption of log normality at the a = 0.01 level of significance. Letting $z_i = (y_i/x_i)$ represent the ith paired ratio of effluent concentration to influent concentration, the assumption that the z_i's follow an approximate log normal distribution implies that the quantities $\log(z_i) = (\log y_i - \log x_i)$ follow an approximate normal distribution. Furthermore, the normal distribution also then describes the behavior of the average of these log ratios:

$$\overline{\log z} = \frac{1}{n}\Sigma_i \log z_i = (\overline{\log y} - \overline{\log x}) \quad (4)$$

and a t-statistic with (n-l) degrees of freedom (where n represents the number of data pairs) can be formed using the expression:

$$t_{n-1} \sim \frac{[\overline{\log z} - \log(1-R_0)]\cdot\sqrt{n}}{S_{\log z}} \quad (5)$$

where R_0 is the developer's claimed or expected removal efficiency and $S_{\log z}$ is the standard deviation of the logged ratios.

This formula was used to develop a confidence interval for the true expected removal efficiency. By rearranging the terms and solving for log (1 $-R_0$), we have the approximate equation :

$$\log(1-R_0) \in \overline{\log z} \pm t_{n-1,a}\cdot\frac{S_{\log z}}{\sqrt{n}} \quad (6)$$

Further exponentiation and rearrangement leads to the final CI expression for R_0:

$$R_0 \in 1-\exp\left[\overline{\log z} \pm t_{n-1,a}\cdot\frac{S_{\log z}}{\sqrt{n}}\right] \quad (7)$$

This was then the expression used to compute the removal a was chosen to be .10, since a "cuts off" one tail of the t-distribution, so that a total of 20% is cut off when the upper and lower confidence limits are computed. Likewise, for 90% confidence, a was chosen to be

One other point should be noted concerning the point estimates of removal efficiency. Rather than simply taking one minus the mean effluent divided by the mean influent, the point estimates were based on the paired samples.

The method used in this case is equivalent to computing one minus the geometric mean of the paired effluent to influent ratios. Explicitly, the following equation was employed:

$$R_o = 1 - \exp[\overline{\log}\ z] \quad (8)$$

This point estimate will generally be slightly different from the typical one minus the mean effluent divided by the mean influent, but it explicitly accounts for the pairing in the data and has much better understood statistical properties.

Process Monitoring

Field and process monitoring data were taken by the developer at a predetermined frequency. These measurements included:

- Microtox™ Soil Toxicity Assays
- Pore Water Monitoring
- Air Sampling
- Soil Temperature Monitoring
- Soil Water Holding Capacity
- Soil Moisture Monitoring
- Greenhouse Ambient Air Temperature
- Greenhouse Air Temperature During Sampling
- Outside Air Temperature

4.4 Performance Data

4.4. I *SITE Contractor Results from Pre-Demonstration*

Pre-demonstration soil samples were collected by the SITE contractor to characterize the target media for treatment and non-treatment; to ensure the presence, concentration, and variability of target compounds (PAHs and PCP) present in the target media; and to identify any possible conditions present in the soil that would inhibit the treatment process or its validation (i.e., oversized particles, dioxins/furans, metals, volatile organics, pesticides, and PCBs). Analysis of the pre-demonstration data from each plot indicated concentrations of target contaminants acceptable to the developer, and a possible inhibitor to the evaluation process.

The Treatment Plot exhibited total PAH concentrations ranging from 2274 mg/kg to 3453 mg/kg and TCP concentrations ranging from 540 mg/kg to 740 mg/kg. The No-Treatment Plot exhibited total PAH concentrations of 1772 mg/kg and TCP concentrations of 360 mg/kg. PCPl was the only chlorinated phenol detected in both plots. The only VOC detected was acetone, which may have been a laboratory artifact. Pm-demonstration soil data for organic compounds only utilized soil samples sieved to less than 0.5 inches in diameter.

According to the developer, no inhibitors were evident in the demonstration soils. The test soil had been previously screened by the developer to a diameter of 2 inches. No abundant concentrations of toxic heavy metals were evident in either plot. Pesticides, PCBs, and carcinogenic dioxins were not detected in the Treatment Plot. The No-Treatment Plot soil was not analyzed for pesticides, PCBs, or dioxin/furans.

An important physical observation made during the pre-demonstration was the abundance of oversized material (greater than 1 inch in diameter) as supported by the results of the particle size distribution analysis of the soil in each plot. The developer had screened the ex situ soil previous to sampling to a particle size of approximately 4 inches. The particle size distribution analysis indicated that the Treatment Plot soils exhibited 13% fines, 26% sand, and 61% gravel or larger. Particles larger then gravel size comprised 51% of the total soil sample. The abundance of this oversized material would potentially bias the evaluation and would require additional analyses to correct. Discussions with the developer resulted in the soil from the two plots being removed and re-screened to less than 1 inch in diameter and replaced into the plots prior to the start of the demonstration.

In addition, to enhance the evaluation of the technology, the laboratory screened the composite samples to a 1-inch particle size and analyzed representative subsamples for SVOCs. The concentrations and variations observed during pre-demonstration activities were used to support assumptions made in developing the demonstration's experimental design.

4.4.2 Summary of Results - Primary Objectives

Results from the SITE demonstration indicate that the DARAMEND™ Bioremediation Technology significantly reduced total PAHs and TCP during the period of treatment (254 days) in the Treatment Plot. The primary objective was established by comparing the sums of the concentrations of select PAHs and of CPs from the excavated wood-treatment soils within the Treatment Plot prior to the application of the DARAMEND™ Technology and at the end of approximately 8 months (254 days) of treatment.

Total PAHs were reduced from an average of 1710 mg/kg to 98 mg/kg, a 94% reduction with a 90% Cl of 93.4 to 95.2%; TCP were reduced from an average of 352 mg/kg to 43 mg/kg, an 88% reduction with a 90% Cl of 82.9 to 90.5%. Table 4-l summarizes the performance of the DARAMEND™ Bioremediation Technology over the course of the SITE demonstration. Figure 4-4 graphically depicts the performance of the primary objectives.

It should be noted that during the statistical treatment of the Treatment Plot data no outliers were detected and thus excluded from the analyses. Six constituents were consistently non-detected during both sampling events and could not be statistically analyzed for this reason. These include:

2-Chlorophenol, 2,4-Dichlorophenol, 2,4,6-Trichlorophenol, 2,4,5 Trichlorophenol, Naphthalene, and Acenaphthylene. To calculate removal efficiencies of TCP and total PAHs in light of these non-detected compounds, three different cases were constructed: 1) putting all NDs at the MDL, 2) putting all NDs at half the MDL, and 3) putting all NDs at 0. All three cases gave very similar results, concluding that the treatment of non-detects in this particular dataset is not a significant issue. Using the statistical methodology described in Section 4.3.3, point estimates, R, for % reductions in the geometric mean concentrations of total PAHs and total chlorophenols, and their respective Cls were computed and are presented below.

These results indicate that with a 90% level of confidence (i.e., 10% chance of error) total PAHs and total chlorinated were reduced by 93.7% or more and 84% or more, respectively, in the Treatment Plot over a period of 254 days.

Supporting documentation is presented in Appendix B of the TER, which includes descriptive analyses of the set of ratios for each compound examined on a log scale as well as histograms and probability plots, descriptive statistics, and the results of a Shapiro-Wilk test of normality (which on the log scale tests the original ratios for log-normality).

4.4.3 Summary of Results - Secondary Objectives

4.4.3.1 **The Magnitude of Reduction in the Sums of the Concentration of Select PAHs and Chlorinated Phenols in the No-Treatment Plots Soils**

Results from the SITE demonstration indicate that no significant reduction in TCP occurred during the demonstration in the No-Treatment Plot. This secondary objective was evaluated by comparing the sums of the concentrations of the CPs from the excavated wood-treatment soils within the No-Treatment Plot over the approximately 8 months (254 days) of no-treatment.

Parameter	R	80% Cl	90% Cl
Total PAHs(1)	.946	(.939, .952)	(.936, .954)
Total PAHs(2)	.945	(.938, .951)	(.935, .953)
Total PAHs(3)	.944	(.937, .951)	(.934, .952)
Total Chlorophenols(1)	.906	(.885, .922)	(.878, .927)
Total Chlorophenols(2)	.893	(.869, .913)	(.861, .918)
Total Chlorophenols(3)	.872	(.840, .898)	(.829, .905)

TCP remained at an approximate average of 217 mg/kg. However, total PAHs were reduced from an average of 1,312 mg/kg to 776 mg/kg, a 41% reduction with a 90% Cl of 34.6 to 48.7%. Table 4-l summarizes the performance of the DARAMEND™ Bioremediation Technology over the course of the SITE demonstration. Figure 4-4 graphically presents the performance of this secondary objective. It should be noted that during the statistical treatment of the No-Treatment Plot data no outliers were detected and thus excluded from the analyses.

4.4.3.2 **The Magnitude of Reduction for Specific PAHs and Chlorinated Phenolic Compounds Within Each Demonstration Plot**

Results from the SITE demonstration indicate that the DARAMEND™ Bioremediation Technology reduced (moderately to significantly) all the targeted PAHs and CPs during the period of treatment (254 days) in the Treatment Plot. The secondary objective was accomplished by comparing the sums of the concentrations of each PAH and of each chlorinated phenol from the excavated wood-treatment soils within the Treatment Plot, prior to the application of the DARAMEND™ Technology and at the end of approximately eight months (254 days) of treatment.

Treatment Plot

The reduction of specific PAHs ranged from approximately 98% for acenaphthene to approximately 41% for benzo(g,h,i)perylene. The only targeted chlorinated phenol detectable in the Treatment Plot was PCP. The reduction of PCP was approximately 88% which was reduced from an average of 352 mg/kg to 43 mg/kg. Table 4-2 summarizes the performance of each individual target compound treated by the DARAMEND™ Bioremediation Technology over the course of the SITE demonstration.

The analysis of the Treatment Plot's PAH data indicates that the DARAMEND™ Bioremediation Technology produced significant reductions of 3-ringed and 4-ringed PAH compounds (both averaged approximately 97%), with lower reductions for 5-ringed and 6-ringed PAH compounds (average approximately 77% and 40%, respectively). Figures 4-5 and 4-6 demonstrate the reduction per each of the 3-ringed, 4-ringed, 5-ringed, and g-ringed PAH compound groups. No statistical analysis was required to support these conclusions on the Treatment Plot results for specific PAHs and CPs, however, a statistical analysis was performed as a byproduct of the analysis of total PAHs and TCP in Section 4.4.2. This analysis is presented below.

A statistical analysis of the demonstration's specific PAHs and CPs from the baseline soil sampling event (Event #0, 0 days of treatment) and the final soil sampling event (Event #3, 254 days of treatment) was utilized to calculate the point estimates for average removal and associated levels of significance and confidence intervals. The statistical approach was the same utilized for the evaluation of the primary objective (see Section 4.4.2).

Six constituents were consistently non-detect during both sampling events and could not be statistically analyzed for this reason. These include 2-Chlorophenol, 2,4-Dichlorophenol, 2,4,6-Trichlorophenol, 2,4,5-Trichlorophenol,

Table 4-1 Primary and Secondary Objective Results for Total PAHs and TCP

GRACE Bioremediation Technologies
Daramend™ Bioremediation Treatment Process
Trenton, Ontario, Canada

(Concentrations in mg/kg)

	Treatment Plot Days of Treatment					No-Treatment Plot Days of No-Treatment				
Analyte	0	88	144	254	Percent Removal	0	88	144	254	Percent Removal
Total PAHs	1710	619	221	98	94.3	1312	1155	982	776	40.9
TcPAHs	390	250	123	54(43)[1]	86.1(89.0)[1]	377	338	309	274	27.1
TB(a)PEQ	55	59	31	15(11)[1]	72.4(80.3)[1]	62	56	62	45	26.7
TCPs	352	158	90	43	87.8	217	288	356	218	0

All data is mg/kg on a dry weight basis
TPAHs - Total Polynuclear aromatic Hydrocarbons
TcPAHs - Total Carcinogenic Polynuclear Aromatic Hydrocarbons
TB(a)PEQ - Total Benzo(a)Pyrene Equivalents
TCPs - Total Chlorinated Phenols
l-Data provided by Grace Bioremediation Technologies based on analyses of split samples by an independent laboratory.

Note: Percent removals presented in this table have been calculated using the arithmetic average (mean) concentrations from Events 0 (day 0) and 3 (day 254).

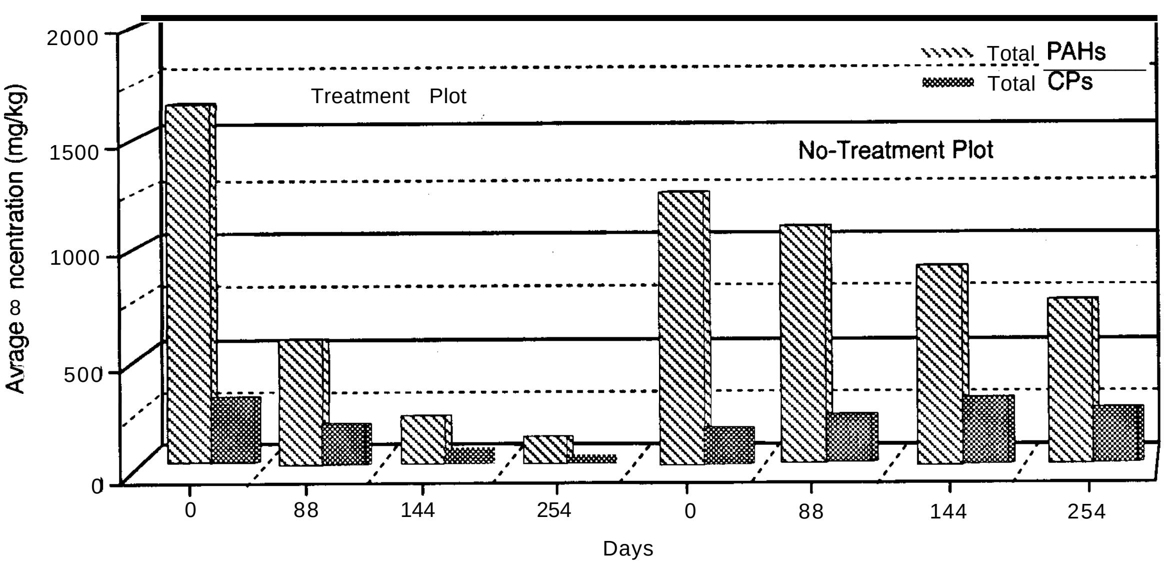


Figure 4-4. Primary and Secondary Objective Results Total and TCP.

Table 4-2. Specific Results for Each PAH and Chlorinated Phenol Compound Detected in the Treatment Plot

GRACE Bioremediation Technologies
DARAMEND™ Bioremediation Treatment Process
Trenton, Ontario, Canada

Treatment Plot
(Concentrations in mg/kg)

Compound	Compound Type	Event 0 Average Concentration	Event 1 Average Concentration	Event 2 Average Concentration	Event 3 Average Concentration	Percent Removals	Average Percent Removals
Pentachlorophenol	Chlorinated Phenol	350.00	160.0	90.0	43.00	87.7	87.7
Fluorene	3-Ring PAH	43.0	36.2	4.1	1.16	97.3	97.1
Acenaphthene	3-Ring PAH	62.0	34.4	3.9	0.99	98.4	
Phenanthrene	3-Ring PAH	190.0	20.0	4.7	3.60	98.1	
Anthracene	3-Ring PAH	70.0	14.0	5.4	4.70	93.3	
Fluoranthene	4-Ring PAH	550.0	120.0	34.0	13.00	97.6	97
Pyrene	4-Ring PAH	390.0	120.0	34.0	11.00	97.2	
Benzo(a)anthracene	4-Ring PAH	80.0	25.0	8.2	3.80	95.3	
Chrysene	4-Ring PAH	120.0	50.0	17.0	6.80	94.3	
Benzo(b)fluoranthene	5-Ring PAH	61.0	59.0	41 .o	15.00	75.4	77.1
Benzo(k)fluoranthene	5-Ring PAH	66.0	50.0	19.0	6.70	89.8	
Benzo(a)pyrene	5-Ring PAH	39.0	38.0	21.0	10.00	74.4	
Indeno(l,2,3-cd)pyrene	5-Ring PAH	17.0	16.0	12.0	9.10	46.5	
Dibenz(a,h)anthracene	5-Ring PAH	6.5	12.3	4.6	2.60	70.5	
Benzo(g,h,i)perylene	6-Ring PAH	16.0	15.0	11.0	9.50	40.8	40.6

Note: Percent removals presented in this table have been calculated using the arithmetic average (mean) concentrations from Events 0 (day 0) and 3 (day 254).

Naphthalene, and Acenaphthylene. To calculate total chlorophenols and total PAHs in light of these nondetected compounds, three different cases were constructed: 1) putting all NDs at the MDL, 2) putting all NDs at half the MDL, and 3) putting all NDs at 0. All three cases gave very similar results, concluding that the treatment of non-detects in this particular dataset is not a significant issue.

One other non-detect sample occurred during Event #0 for constituent Dibenzo(a,h)anthracene. The MDLof 47,300 mg/kg for this sample is very high relative to the other detected concentrations for this compound in the pretreatment (all of which were no greater than 11,000). Furthermore, all the post-treatment samples contained this compound at similar levels. Avalue equal to the average of the other pre-treatment sample values for this constituent was utilized, a method often used for missing data values. Although the data value was not missing, it does appear somewhat anomalous.

Given all these considerations, point estimates for average removal (R) and the associated Cl are presented below:

Parameter	R	80% Cl	90% Cl
Pentachlorophenol	.872	(.840, .898)	(.829, .905)
Acenaphthene	.986	(.983, .989)	(.982, .989)
Fluorene	.979	(.973, .983)	(.971, .985)
Phenanthrene	.981	(.978, .984)	(.977, .985)
Anthracene	.942	(.929, .952)	(.924, .955)
Fluoranthene	.977	(.974, .980)	(.973, .981)
Pyrene	.974	(.970, .977)	(.969, .978)
Benzo(a)anthracene	.954	(.949, .959)	(.947, .960)
Chrysene	.946	(.940, .952)	(.938, .954)
Benzo(b)fluoranthene	.773	(.740, .802)	(.729, .810)
Benzo(k)fluoranthene	.902	(.888, .914)	(.884, .918)
Benzo(a)pyrene	.749	(.717, .777)	(.707, .785)
Indeno(l,2,3-cd)pyrene	.470	(.391, .539)	(.364, .559)
Dibenz(a,h)anthracene	.618	(.565, .664)	(.548, .677)
Benzo(g,h,i)perylene	.454	(.339, .550)	(.299, .575)

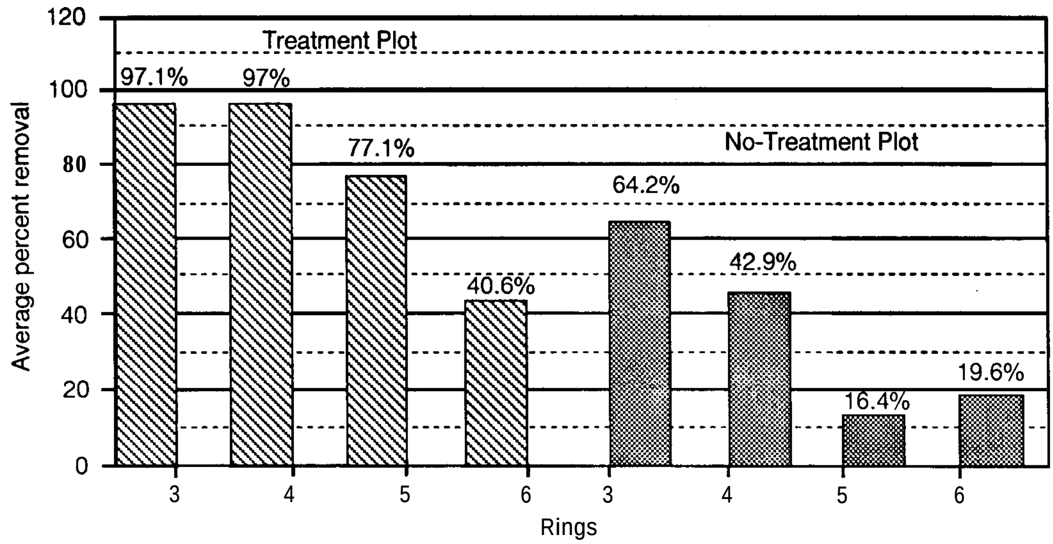


Figure 4-5. PAH Percent Removal By Number of Flings.

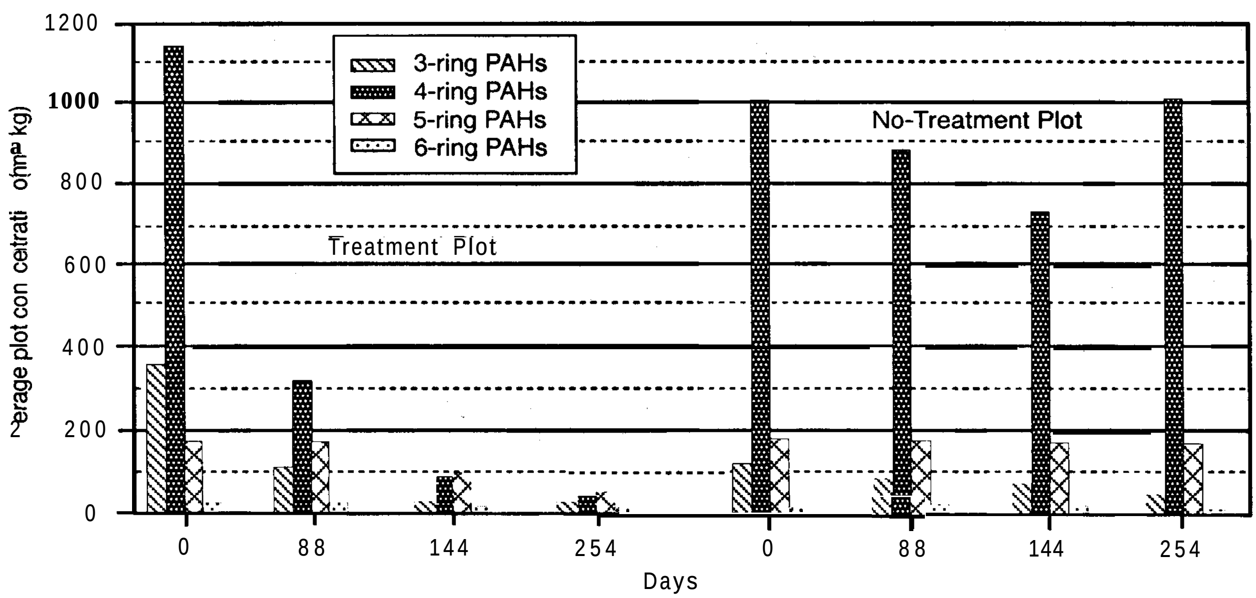


Figure 4-6. PAH Concentration By Number of Rings.

As discussed above, based on the estimated Cl, the developer's claim can be said to be supported by statistical hypothesis testing at the .10 significance level for acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, and chrysene. None of the other tested compounds meet the claim at this level of significance.

Supporting documentation is presented in the TER, which includes a descriptive analyses of the set of ratios for each compound examined on a log scale as well as histograms and probability plots, descriptive statistics, and the results of a Shapiro-Wilk test of normality (which on the log scale tests the original ratios for log normality).

No-Treatment Plot

The reduction of specific PAHs ranged from approximately 76% for fluorene to approximately -14% for benzo(b)fluoranthene. The only targeted chlorinated phenol detectable in the No-Treatment Plot was PCP. No significant reduction of PCP was encountered (average baseline concentration of 216.7 mg/kg in comparison with an average final concentration of 217.5 mg/kg). Table 4-3 summarizes the performance of each individual target compound left untreated by the DARAMEND™ Bioremediation Technology over the course of the SITE demonstration.

4.4.3.3 *Comparison of Performance of Treatment Plot vs. No-Treatment Plot*

Statistical comparisons with respect to individual and total PAHs, and individual and total chlorophenols were performed to establish if the point estimates of contaminant removal efficiencies computed for the Treatment Plot were significantly different from those computed for the No-Treatment Plot. These comparisons were made with a 10% level of significance and the results are presented in Table 4-4. Results of this analysis indicate that by day 254 (i.e., sampling Event 3) of the demonstration study the percent reductions in the geometric mean concentrations of all detected target contaminants in the Treatment Plot (except for Dibenz(a,h)anthracene) were significantly higher than those realized in the NoTreatment Plot. For Dibenz(a,h)anthracene, the reductions in the two plots by day 254 were statistically indifferent. This may have been due to the inherent limitations associated with low initial concentrations (around 10 mg/kg) in both soils. With respect to the two critical parameters, total PAHs and TCP, through all three subsequent sampling events (1,2, and 3) of the study the reductions realized in the Treatment Plot were significantly higher than those in the No-Treatment plot.

4.4.3.4 *The Toxicity of the Soil to Earthworms and Seed Germination in Each of the SITE Demonstration Plots Before and After Treatment*

Toxicity tests were performed on the pre- and post-remediation soil samples to determine if the toxicity of the soil had decreased due to the degradation of the compounds of interest. Two toxicity tests, germination of lettuce and radish seeds and earthworm survival, were used to evaluate the efficacy of the DARAMEND™ Bioremediation Technology in soils contaminated with CPs and PAHs. This battery of tests was conducted on untreated and DARAMEND™ treated, pre-and post-remediation samples of contaminated soil. In addition, negative and positive controls were utilized as part of the testing regime. Both controls were used to assess the health of the test organisms; the positive control would produce an observable effect. The positive control response should also be within two standard deviations of the running mean of the positive control response as determined from a control chart tracking recent positive control tests. If either the negative or positive control response was outside acceptable levels as indicated in the DQOs (i.e., negative control survival is 80% or positive control response is two standard deviations away from running mean), the health of the test organisms must be examined and the tests may need to be conducted again. The seed germination toxicity testing utilized lettuce (Lactuca sativa) and radish *(Raphanus sativus).* The earthworm toxicity tests utilized the red worm *(Eisenia foetida).* Each of the test species was routinely used in the evaluation of contaminated soils.

In all tests of 100% pre-treatment soil (i.e., untreated and DARAMEND™ treated soil from Event #O), the endpoints of interest for a particular test species were depressed relative to negative controls. The endpoints of interest were plant germination and earthworm survival. For example, 50% inhibition of lettuce and radish seed germination prior to remediation was calculated to occur in soil mixtures containing approximately 4% and 60% of the contaminated soil, respectively, while the concentration of contaminated soil required to kill 50% of the earthworms was calculated to be approximately 25%.

The DARAMEND™ Bioremediation Technology appeared to reduce the toxicity of the contaminated soil to both the plant seeds and the earthworms in the Treatment Plot. Post-remediation toxicity of the untreated, contaminated soil in the No-Treatment Plot to the earthworms was only slightly decreased while the DARAMEND™-treated, contaminated soil was essentially non-toxic. The slight reduction in toxicity of the No-Treatment Plot soils is consistent with the slight reductions in PAHs observed. Similarly, the inhibition of seed germination post-remediation was only slightly reduced in the untreated, contaminated soil while the 100% DARAMEND™-treated, contaminated soil treatments caused 0% and 33% inhibition of germination for radish and lettuce seeds, respectively. Negative and positive control samples included within the testing scheme were within acceptable limits and the toxicity testing analyses conformed to all appropriate QA/QC requirements. Table 4-5 and 4-6 present the results of the toxicity tests.

Table 4-3. Specific Results for Each PAH and Chlorinated Phenol Compound Detected in the No-Treatment Plot

GRACE Bioremediation Technologies
DARAMEND™ Bioremediation Treatment Process
Trenton, Ontario, Canada

No-Treatment Plot
(Concentrations in mg/kg)

Compound	Compound Type	Event 0 Average Concentration	Event 1 Average Concentration	Event 2 Average Concentration	Event 3 Average Concentration	Percent Removals	Average Percent Removals
Pentachlorophenol	Chlorinated Phenol	216.7	288.3	355.0	217.5	-0.4	-0.4
Fluorene	3-Ring PAH	14.4	34.5	23.1	3.5	75.7	64.2
Acenaphthene	3-Ring PAH	23.5	15.8	16.8	7.1	‘69.8	
Phenanthrene	3-Ring PAH	37.2	16.2	15.3	15.0	59.7	
Anthracene	3-Ring PAH	30.8	16.3	12.2	12.3	60.1	
Fluoranthene	4-Ring PAH	461.7	416.7	315.0	185.5	59.8	42.9
Pyrene	4-Ring PAH	355.0	303.3	276.7	270.0	23.9	
Benzo(a)anthracene	4-Ring PAH	75.2	65.2	52.5	44.3	41.1	
Chrysene	4-Ring PAH	117.0	99.0	84.0	76.0	35.0	
Benzo(b)fluoranthene	5-Ring PAH	58.5	56.5	53.7	66.8	-14.2	16.4
Benzo(k)fluoranthene	5-Ring PAH	58.4	55.2	49.8	38.8	38.9	
Benzo(a)pyrene	5-Ring PAH	36.8	35.3	31.2	32.3	12.2	
Indeno(l,2,3-cd)pyrene	5-Ring PAH	14.6	15.0	14.5	12.1	17.1	
Dibenz(a,h)anthracene	5-Ring PAH	16.1	11.9	23.1	4.1	74.5	
Benzo(g,h,i)perylene	6-Ring PAH	13.8	13.8	13.8	11.1	19.6	19.6

Note: Percent removals presented in this table have been calculated using the arithmetic average (mean) concentrations from Events 0 (day 0) and 3 (day 254).

Table 4-4. Summary of Statistical Analysis of Contaminant Reductions in the Treatment and No-Treatment Plots

	Percent Reductions in Geometric Mean Concentractions								
	@ Event 1			@ Event 2			@ Event 3		
Contaminant of Concern	Treatment Plot		No-Treatment Plot	Treatment Plot		No-Treatment Plot	Treatment Plot		No-Treatment Plot
Acenaphthene	49.3	==	46.0	95.8	>>	31.4	98.4	>>	84.3
Fluorene	16.4	>>	0.0	92.7	>>	0.0	97.9	>>	79.1
Pentachlorophenol	54.5	>>	0.0	73.3	>>	0.0	87.2	>>	0.0
Phenanthrene	90.9	>>	55.0	97.4	>>	56.8	98.1	>>	68.2
Anthracene	81.4	>>	50.5	92.3	>>	63.3	94.2	>>	62.7
Fluoranthene	80.2	>>	8.4	94.7	>>	31.3	97.7	>>	62.2
Pyrene	71.8	>>	22.4	92.6	>>	29.4	97.4	>>	30.8
Benzo(a)anthracene	71.6	>>	15.3	90.4	>>	31.7	95.4	>>	42.3
Chrysene	60.7	>>	16.8	86.7	>>	29.3	94.6	>>	35.9
Benzo(a)fluoranthene	4.2	==	1.7	33.6	>>	6.6	77.3	>>	0.0
Benzo(k)fluoranthene	25.1	>>	8.8	73.1	>>	17.7	90.2	>>	36.4
Benzo(a)pyrene	4.0	==	4.7	48.0	>>	15.7	74.9	>>	12.2
Indeno(1,2,3-cd)pyrene	3.0	==	0.0	27.1	>>	1.3	47.0	>>	18.5
Dibenz(a,h)anthracene	0.0	<<	29.5	30.0	>>	0.0	63.0	==	60.0
Benzo(g,h,i)perylene	7.5	==	1.4	26.8	>>	1.0	45.4	>>	21.9
Total PAHs	64.4	>>	14.5	87.6	>>	27.4	94.4	>>	42.0
Total Chlorophenols	54.5	>>	0.0	73.3	>>	0.0	87.2	>>	0.0

Note: Results of Statistical Comparisons between reductions of a given contaminant in the Treatment Plot and that in No-Treatment Plot with a 90% Level of Confidence are presented in the Table above using signs described below.
">>" Implies that the reduction of the contaminant in the Treatment Plot was Significantly Higher than that in the No-Treatment Plot.
"==" Implies that the reductions of the contaminant in the Treatment and No-Treatment Plots were Statistically Indifferent or the Same.
"<<" Implies that the reduction of the contaminant in the Treatment Plot was Significantly Lower than that in the No-Treatment Plot.

4.4.3.5 The Fate of Total Recoverable Petroleum Hydrocarbons in Each of the Demonstration Plots

The results of the SITE demonstration concerning total recoverable petroleum hydrocarbons (TRPH) indicated a significant reduction occurred in the Treatment Plot and no significant reduction occurred in the No-Treatment Plot. In the Treatment Plot, TRPHs were reduced from 7,300 mg/kg to 932 mg/kg (87% reduction approximately). In the No-Treatment Plot, TRPHs remained at approximately 5,000 mg/kg. This secondary objective was evaluated by comparing the results of the TRPH analyses of the targeted soils in both plots at the beginning and end of the approximately 8 months (254 days) of study during the SITE demonstration. Table 4-7 and Figure 4-7 exhibit the TRPH results for the SITE demonstration.

4.4.3.6 General Soil Conditions - Inhibitors/ Promoters to Technology's Effectiveness

Table 4-5. Mortality of the earthworm, *Eisenia foetida*, from 28 day soil toxicity tests. Values reported are the mean percent mortality in the 100% treated and untreated soil before and after remediation. Paired negative control mortality is in parentheses.

	Mean Percent Mortality	
	DARAMEND™ Treated Soil	Untreated Soil
Baseline (October 1993)	100% (0%)	100% (0%)
Post-Treatment	0% (3%)	100% (3%)

Table 4-6. Inhibition of germination from 5 day soil toxicity tests conducted with lettuce (Lactuca sativa) and radish (Raphanus *sativus).* Values reported are the mean inhibition of germination in 100% untreated and treated soil before and after remediation. Paired negative control inhibition of germination is in parentheses.

Mean Percent Inhibition of Germination

	Daramend™ Treated Soil		Untreated Soil	
Radish	Lettuce	Radish	Lettuce	
Baseline (October 1993)	100% (8%)	52% (4%)	97% (5%)	82% (9%)
Post-Treatment (September 1994)	33% (5%)	0% (1%)	92% (5%)	23% (1%)

Based on the significant reduction of total PAHs and TCP in the Treatment Plot soils, no inhibitors to the activity and longevity of degrading microorganisms in the treatment soil were evident. Supportive analytical results indicated that the soil chemistry at the demonstration site caused no negative effect to limit the rate at which biodegradation of PAHs and CPs occurred. Soil chemistry was acceptable to promote significant biodegradation in the Treatment Plot. PSD results are discussed in Section 4.4.4.

Presence of Inhibitors to Biodegradation

The developer's literature indicates that soil containing a high concentration of heavy metals and having a high acidity, may limit the biodegradation rate of the DARAMEND™ Bioremediation Technology. Soil sample composites for metals analysis were collected in both plots initially (day 0) and at the end of the demonstration (day 254). No significant change occurred in the concentration of metals in the soil as a result of the treatment process. A significant reduction of PAHs and CPs in the Treatment Plot soils was exhibited despite the concentrations of metals detected. The various metals present in the soil exhibited the following concentration ranges in mg/kg: Aluminum 3100-3800; Antimony 11.9-<12; Arsenic 4.8-6.4; Barium 39.8-<40; Beryllium <1.0-l .0; Cadmium 0.99-<1 .O; Calcium 140,000-l 67,000; Chromium 8.1 17.7 mg/kg; Cobalt 9.9-l 0; Copper 9.8-l 7.2; Iron 4100-6690; Lead 7.9-19.9; Magnesium 3400-4200; Manganese 150 188; Nickel <0.1 -8.0; Potassium 995-<1000; Selenium 98.8-99.5; Silver Q.O-2.0; Thallium <2.0; Sodium 995-<1000; Vanadium <1 O-l 0; and Zinc 61-l 25. The pH levels in the Treatment Plot ranged from 8.16 to 9.38 during the demonstration. The pH levels in the No-Treatment Plot ranged from 8.28 to 9.5 during the demonstration.

Single soil samples were obtained and analyzed for various chlorinated dioxins and furans at the outset of the project and after 254 days of treatment. Law concentrations of various penta-, hexa, and hepta congeners were present in both samples; the major constituents present were the fully chlorinated congeners, however, the toxic congener 2,3,7,8TCDD was absent in both events, as seen in Table 4-8.

The small differences in the concentration of congeners between the two samples are probably more correctly attributed to sampling variability, rather than to any changes resulting from the DARAMEND™ Bioremediation Treatment. Decreases in totals for tetra-, hexa, hepta, and octa-congeners would, if anything, lead one to suspect that a decrease has occurred over the course of the demonstration.

Presence of Promoters of Biodegradation

According to the developer, the DARAMEND™ Bioremediation Technology provides nutrients to enhance the biodegradation rate of the PAHs and CPs in the demonstration soil. The analytical results for the analysis of chloride, nitrate-nitrite, phosphate, TKN, TOC, and TIC indicates that soil conditions remained somewhat constant during the demonstration, with some trends. TIC appears to be slightly higher in the Treatment Plot compared to the No-Treatment Plot. Otherwise, no differences in these parameters were evident between the Treatment and No-Treatment Plots.

Chloride ranged from 83 mg/kg to 283 mg/kg in the Treatment Plot compared to 20 mg/kg to 139 mg/kg in the No-Treatment Plot. TKN ranged from 234 mg/kg to 450 mg/kg in the Treatment Plot compared to 137 mg/kg to 442 mg/

Table 4-7. Results of Total Recoverable Petroleum Hydrocarbon Analysis

Grace Bioremediation Technologies
DARAMEND™ Bioremediation Treatment Process
Trenton, Ontario, Canada

(Concentrations in mglkg)

Analyte	Treatment Plot Days of Treatment				Percent Removal	No-Treatment Plot Days of No-Treatment				Percent Removal
	0	88	144	254		0	88	144	254	
TRPH	7300	NA	NA	932	87.3	5000	NA	NA	5200	0

NA - Not Analyzed TRPH - Total Recoverable Petroleum Hydrocarbons

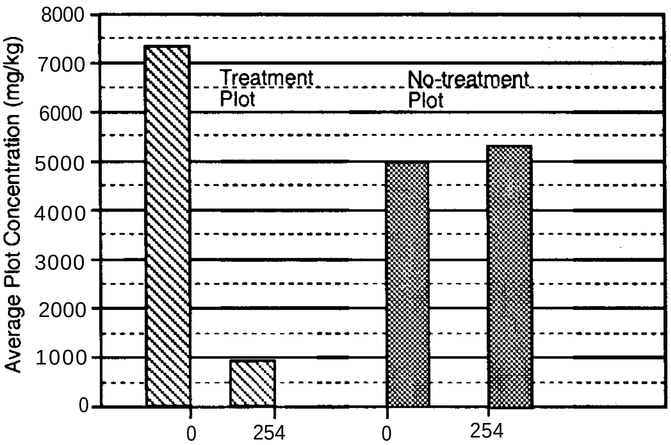


Figure 4-7. Results of Total Recoverable Petroleum Hydrocarbon Analysis (TRPH).

kg in the No-Treatment Plot. Nitrate and nitrite levels were from non-detect to 0.8 mg/kg to 0.3 mg/kg, respectively, in both plots. Phosphates ranged from 2 mg/kg to 1090 mg/kg in the Treatment Plot compared to non-detect to 985 mg/kg in the No-Treatment Plot. TOC ranged from 58,000 mg/kg to 83,300 mglkg in the Treatment Plot compared to 67,000 mg/kg to 79,400 mg/kg in the No-Treatment Plot. TIC ranged from 26,300 mg/kg to 216,000 mg/kg in the Treatment Plot compared to 13,800 mg/kg to 96,200 mg/kg in the No-Treatment Plot.

4.4.3.7 *The Possible Generation of Leachate*

No leachate was generated as a byproduct of the DARAMEND™ Bioremediation Technology. Irrigation water was balanced successfully with system demands to avoid the generation of contaminated leachate. Monitored areas beneath the Treatment Plot were free of leachate over the duration of the demonstration. If generated, this leachate would require treatment prior to discharge.

4.4.3.8 Treatment Effects on the Microbial Biomass

Total heterotrophic microbial biomass, as indicated by mean colony forming units (CFU) per gram of soil generally ranged between 1.0×10^6 and 1.0×10^{10} CFU/g among all plots and sampling dates. Figures 4-8 through 4-l 1 illustrate the trends in CFU across sampling dates for two concentrations of standard plate count agar (PCA 10%, 100%) and a basal mineral media (DifCo Bacto Agar) with PCP supplemented at two concentrations (12.5,25 mg/L) as the major nutrient source for microbial growth. Microbial biomass as CFU was similar for both concentrations of PCA media over the course of the study (Figures 4-8 and 4-9). The same observation was also true for both concentrations of PCP-supplemented media (Figures 4-10 and 4-l 1). For each sampling event the mean CFU in the DARAMEND™ Bioremediation Technology treatment soil were always greater than the mean CFU in the no treatment soil, with the exception of the CFU for Event 0 in the 25 mg/L PCP-supplemented media. The mean number of CFU in the PCP supplemented media also was always smaller than the mean CFU in both no treatment and treatment soils treated with the PCA media. Together, these observations seem to indicate that PCP inhibits and the DARAMEND™ Bioremediation Technology treatment increases microbial biomass, as measured by CFU. These observations are based on trends consistently observed in Figures 4-8 through 4-11, however, a great deal of variability is associated with each of the mean values plotted

Table 4-8. Summary Report for GRACE Bioremediation Technologies DARAMEND™ SITE Project: Total DioxinslFurans

Sample Number	0-TPC-039	3-TPC-045
Sampling Event	00	03
Analytes	Conc. (ppb)	Conc. (ppb)
2,3,7,8-TCDD	ND	ND
1,2,3,7,8-PeCDD	ND	0.116
1,2,3,4,7,8_HxCDD	10.2 .	ND
1,2,3,6,7,8-HxCDD	11.8	7.73
1,2,3,7,8,9-HxCDD	1.75	2.22
1,2,3,4,6,7,8-HpCDD	610	406
OCDD	10400	3830
2,3,7,8-TCDF	ND	ND
1,2,3,7,8-PeCDF	ND	ND
2,3,4,7,8-PeCDF	0.142	ND
1,2,3,4,7,8-HxCDF	1.52	1.72
1,2,3,6,7,8-HxCDF	ND	0.437
2,3,4,6,7,8-HxCDF	ND	0.716
1,2,3,7,8,9-HxCDF	1.58	0.477
1,2,3,4,6,7,8-HpCDF	80.4	23.7
1,2,3,4,7,8,9-HpCDF	4.41	2.15
OCDF	733	346
Total TCDD	1.24	ND
Total PeCDD	ND	0.264
Total HxCDD	81.8	45.2
Total HpCDD	1320	890
Total TCDF	0.0832	ND
Total PeCDF	2.19	2.54
Total HxCDF	99.1	42.8
Total HpCDF	508	161

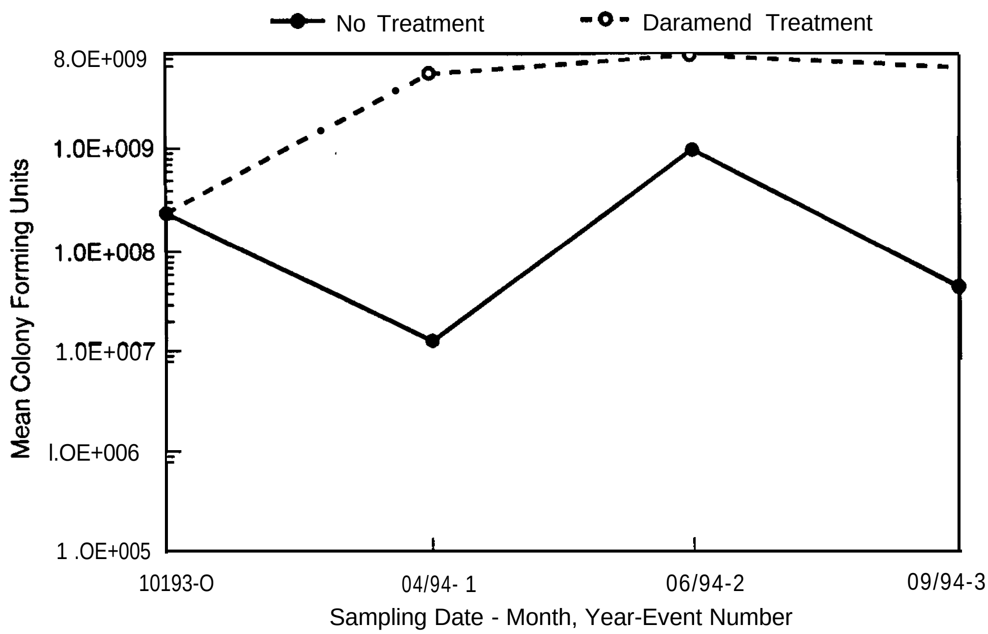


Figure 4-8. CFU/gram soil using 100% PCA agar.

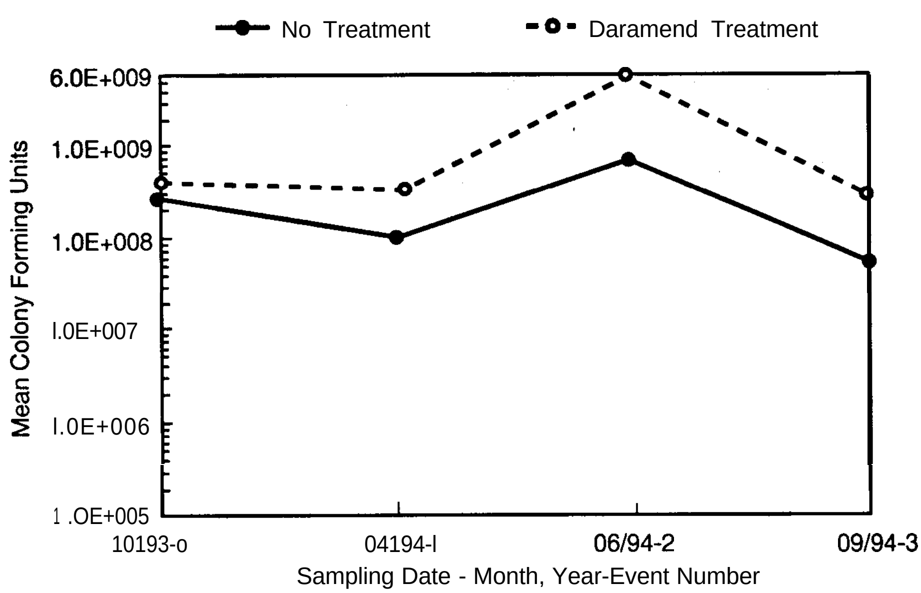


Figure 4-9. CFW/gram soil using 10% PCA agar.

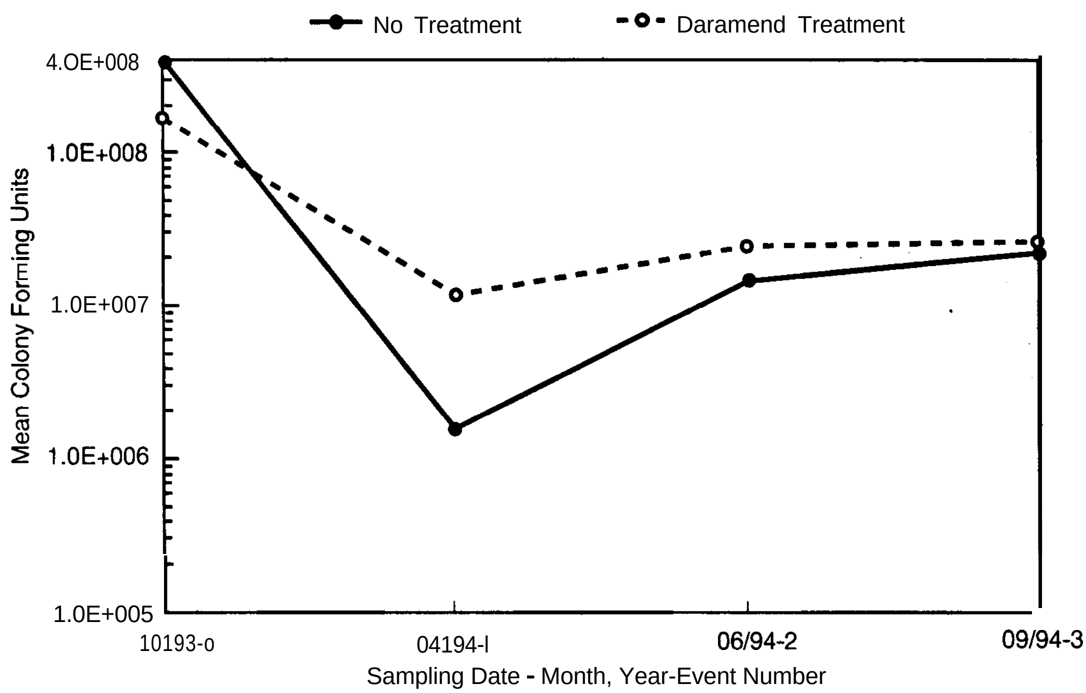


Figure 4-10. CFU/gram soil using 25 mg/L PCP in agar.

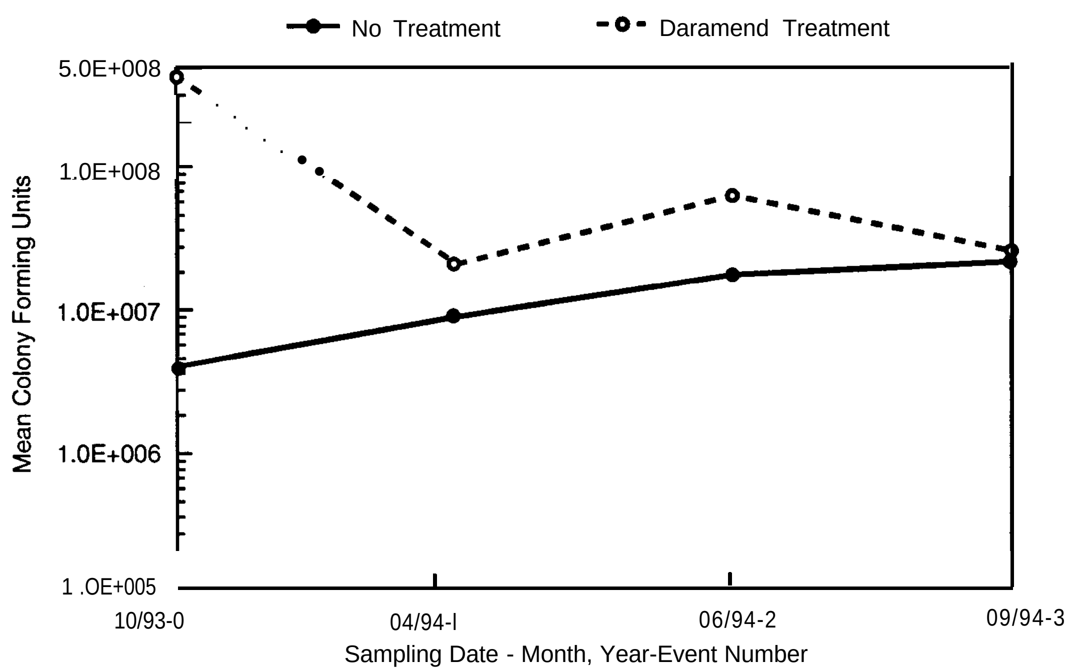


Figure 4-11. CFU/gram soil using 12 PCP in agar.

in these figures. Statistical analysis of the data could indicate that, although they are consistently observed, these trends are not statistically significant.

Comparisons of mean CFUs and concentrations of TCP and total polycyclic aromatic hydrocarbons (TPAH) in untreated and treated soils over time are presented in Figures 4-l 2 through 4-l 5. No discernible trend was obvious in the mean CFU for the no treatment soil even though mean TPAH decreased with time (Figures 4-12 and 4-14). However, mean CFU for the DARAMEND™ Bioremediation Technology treated soil increased over time with a concurrent decrease in both TCP and TPAH concentrations (Figures 4-12 and 4-14). This trend was also supported by an increase in measured soil TIC over time in the DARAMEND™ Bioremediation Technology treated soil. Mean CFU also appeared to increase through time for no treatment soil in the 25 mg/L PCP-supplemented media while little trend was obvious for CFU in DARAMEND™ Bioremediation Technology treated soil (Figures 4-l 3 and 4-l 5). A conservative interpretation of these data would suggest that TPAH concentrations in these soils have an inhibiting effect on microbial biomass in these soils, including organisms that may be capable of metabolizing PCP. This interpretation is supported by the observation that mean CFU for treatment soil increase over time in the 100% PCA media as TCP and TPAH concentrations decrease over time. A large degree of variability (i.e., laboratory's standard deviation) is associated with the mean CFU values presented in Figures 4-12 through 4-15, however, and it is likely that although these trends are consistent and biologically plausible, they may not be statistically significant.

4.4.3.9 *Tendency for the Downward Migration of Contaminants*

The results of monitoring the underlying sand layer beneath the target demonstration soils indicated that the sand layer was contaminated prior to treatment of the demonstration soils and further compromised during the demonstration. The initial contamination of the underlying sand layer occurred when the demonstration soils were removed from the plots, after the pre-demonstration results indicated the soils needed to be re-screened (to exclude particles larger than l-inch). The underlying sand layer was probably partially mixed with the demonstration soils. Secondly, project logbooks indicate that the demonstration soils were further compromised just prior to the demonstration, when a thunderstorm blew off the protective plastic covering on each plot. The greenhouse was not completed when the SITE demonstration started. As a result, rain water saturated parts of each plot. Leachate was evident beneath each plot. Furthermore, during the demonstration the soils in the Treatment Plot were once accidentally mixed with the underlying sand layer prior to April 1994, during a scheduled soil tillage. In conclusion, the tendency for pollutants to migrate downward from the treatment soil is inconclusive since this aspect of the evaluation was compromised.

Baseline total PAHs and TCP present in the underlying sand exhibited concentrations averaging 430 mg/kg and 115 mg/kg, respectively. Final total PAHs and TCP present in the underlying sand exhibited concentrations averaging 101 mg/kg and 54 mg/kg, respectively. Reduction rates for total PAHs and TCP were approximately 77% and 53%, respectively. These results are less significant than those of the demonstration soils in the Treatment Plot and are reported for the curiosity of the reader.

In addition, records from the baseline event indicate that the sand layer was easily differentiated from the demonstration soils based on color. The underlying sand layer exhibited a yellow color, while the demonstration soil exhibited a dark brown color, though one of the three sand samples collected during the baseline event exhibited a dark stain. After May 1994, differentiation based on color was not possible. Sampling was based on targeted depths and proximity to the fiberpad beneath the sand layer.

4.4.4 **Process Operability and Performance**

This section summarizes the operability of the process and overall performance of the DARAMEND™ Bioremediation Technology at the Domtar site. This section includes discussions about developments and problems encountered, along with the manner in which these items were resolved.

The DARAMEND™ Bioremediation Technology operated over a period of 254 days with only a few incidents that deviated from the Demonstration Plan. Otherwise, the process was installed, monitored, and maintained by the developer with regularity as designed and discussed earlier in this section. These incidents that deviated from the original plan are discussed in detail below.

During the pm-demonstration, the soil/sand interface was contrary to the design of the plot: the contaminated soil layer was determined to be only 1 -foot thick as opposed to the 2-foot thickness designed. In addition, a large percentage (about 50%) of oversized material (2 inch to 3/8 inch in diameter) was present in the demonstration soil. This large percentage of oversized material required the soil to be excavated from the plots and re-screened to contain soil particles smaller than 1 inch in diameter to reduce the amount of oversized material.

During the baseline event (Event #O), pre-sampling activities indicated that the depth of the soil layer was variable (ranging from 0.6 feet to 1.3 feet) throughout the Treatment Plot. The variability of the soil's thickness above the underlying sand layer made it impossible to till the soil without mixing the two layers together. An agreement was reached to collect the baseline soil samples from the Treatment Plot after the soil had been tilled to a uniform depth of 12 inches, and amendments had been added. The initial approved approach was to collect soil samples prior to treatment. All subsequent tilling and sampling operations would be confined to a depth of 12 inches.

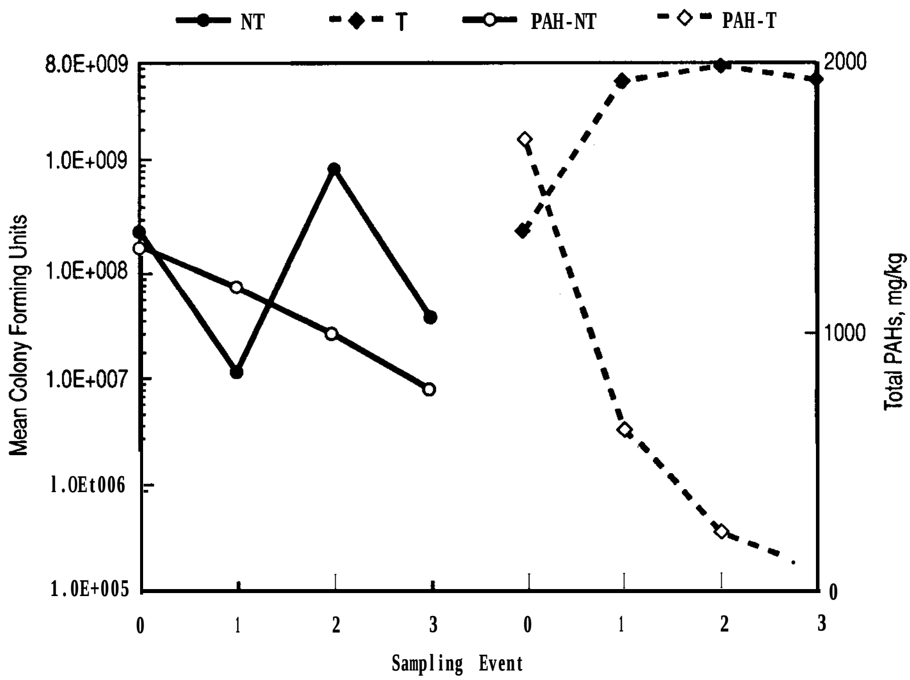


Figure 4-12. CFU/gram soil vs. TPAHs - 100% PCA

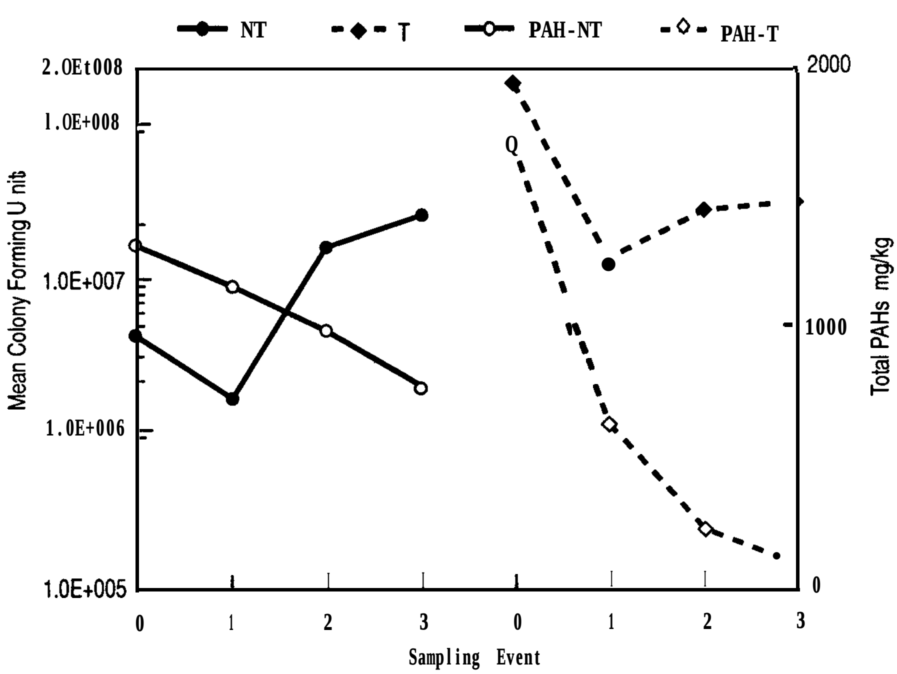


Figure 4-13. CFU/gram soil vs. TPAHs - 25 mg/L PCP.

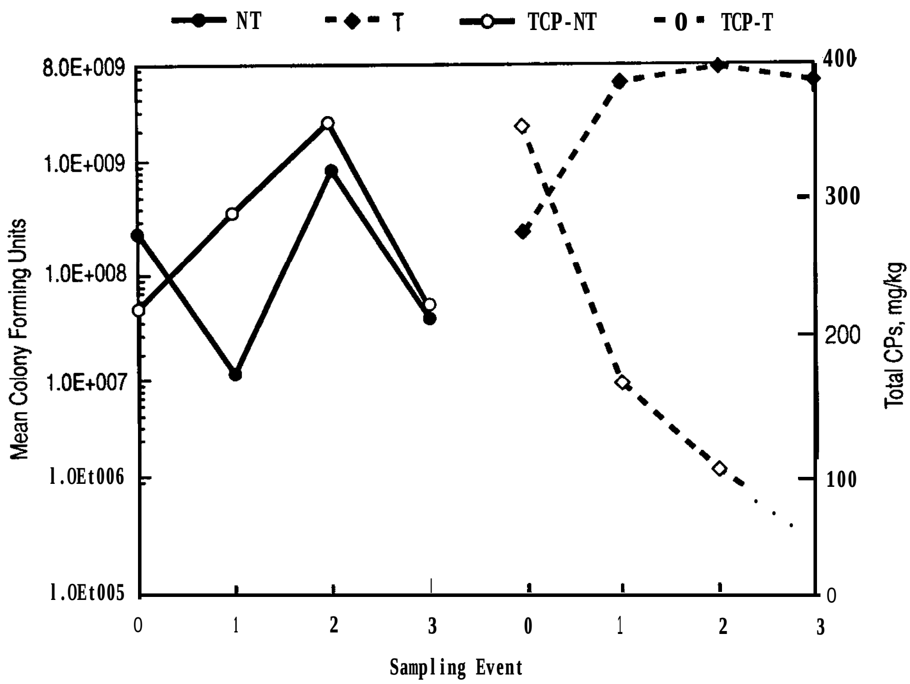


Figure 4-14. CFU/gram soil vs. TCPs - 100% PCA.

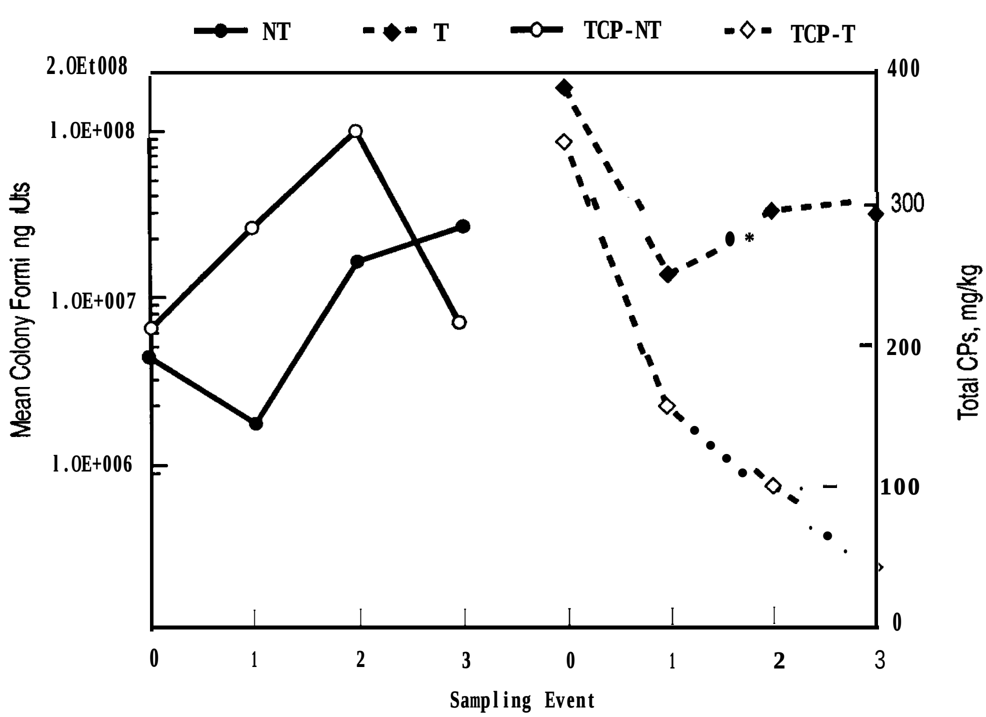


Figure 4-15. CFU/gram soil vs. TCPs - 25 PCP.

During subsequent events #l through #3, sampling of the sand layer indicated that mixing of the two layers may have occurred. The sand layer sampled contained a mixture of sand and soil.

During sampling Event #2, the developer was informed of the soil and sand mixing issue. The developer suspected that the two layers were accidentally tilled together during scheduled plot maintenance. The date of this incident is unclear. This dilution of the demonstration soil by accidental mixing with the sand layer caused a minor interference with the evaluation of the treatment process. The magnitude of the problem was evaluated by comparing the PSD analyses of composite soil samples collected during the baseline and final sampling events. Table 4-9 depicts the results of this analysis. As a result, a 14% increase in the sand size fraction of the demonstration soils was observed by measuring the increase in the amount of sand evident in the Treatment Plot before and after treatment (Event #Cl vs Event #3). This increase in sand size particles in the Treatment Plot is most likely a result of this accidental mixing of these two layers. The overall impact of this incident had no significant impact (i.e., 2% reduction) on the overall performance of the treatment process. The supportive calculations concerning the sand dilution issue are presented below:

Sand Dilution Calculations

To account for the 14% increase in sand-sized particles, the PAH and chlorinated phenol concentrations had to be adjusted. PCP was chosen as an example. The initial (i) and final (f) average concentrations evident in the Treatment Plot were utilized to calculate the percent removals depicted in Scenarios A and B below:

Scenario A - Not Accounting for Dilution via Sand Mixing Incident

If PCP_i = 349 mg/kg and PCP, = 43 mg/kg, as measured in the Treatment Plot.

Then the percent reduction = 1 - Conc./$Conc._i$, hence, 1 - 43 mg/kg / 349 mg/kg = 88% reduction, approximately.

But the "final" sample was in fact diluted by 14% due to the addition of the sand. Therefore, the PCP, would be calculated as 43 mg/kg multiplied by 1 .14 (dilution factor) = 49 mg/kg if there were no sand present. The 14% "additional" test mixture due to the sand has the effect of lowering the final analyte concentration as depicted in Scenario B:

Scenario B - Accounting for 14% Dilution via Sand Mixing Incident

PCP_i = 349 mg/kg , PCP_f = 43 mg/kg

Then the percent reduction = 1 - $Conc._f$ (1.14) / $Conc._i$, hence, 1 - 43 mg/kg (1 .14) / 349 mg/kg = 86% reduction, approximately.

Comparison of the 2% reduction rates indicates an overall significant difference of approximately 2% on the overall performance of the DARAMEND™ Bioremediation Technology on the treatment of PCP.

4.5 Process Residuals

The DARAMEND™ Bioremediation Technology demonstration generated limited residuals. The primary generated waste during the SITE demonstration was oversized particles in the form of wood debris, stone, and construction material that was removed from the targeted test soils prior to bioremediation treatment by a mechanical sieve. These residual soils lacked heavy metals and carcinogenic dioxin compounds. No leachate was generated as a result of the technology's irrigation process. However, as a result of sampling and maintenance/monitoring activities, used personal protection equipment (PPE) and contaminated water from decontamination activities were generated.

Table 4-9. Soil Particle Size Distribution Data

Non-Treatment Composite (NTC):

Fraction	9/93 Pre-Demo	10/93 Event 0	Events: "Pre to 0" Difference	10/94 Event 3	Events: "0 to 3" Difference
(Finer)	-12%	-22%	+IO%	-21%	-1%
Fine Sand	-7%	-13%	+6%	-13%	—
Medium Sand	-10%	-15%	+5%	-18%	+3%
Coarse Sand	-10%	-10%	—	-15%	+5%
Fine Gravel	-10%	-5%	-5%	-8%	+3%
(Coarser)	-50%	-32%	-18%	-22%	-10%

The amount of gravel decreased 23% between the pre-demo sampling and Event 0. The NTC sample showed an 11% increase in the sand fractions between the pre-demo sampling and Event 0, and an 8% increase over the course of the demonstration. The amount of finer particles increased by about 10% before the demonstration, and decreased by about 1% between Event 0 and Event 3.

Treatment Plot Composite (TPC):

Fraction	9/93 Pre-Demo	10/93 Event 0	Events: "Pre to 0" Difference	10/94 Event 3	Events: "0 to 3" Difference
(Finer)	-13%	-15%	+2%	-25%	+IO%
Fine Sand	-8%	-10%	+2%	-15%	+5%
Medium Sand	-10%	-15%	+5%	-20%	+5%
Coarse Sand	-8%	-11%	+3%	-15%	+4%
Fine Gravel	-10%	-8%	-2%	-8%	—
(Coarser)	-51%	-40%	-11%	-15%	-25%

Gravel decreased 13% between the predemo and Event 0, and decreased 25% during the demonstration. The TPC sample showed a 10% total increase in the sand fractions between the pre-demo sampling and Event 0, and a 14% increase over the course of the demonstration. The amount of finer particles also increased, by about 2% before the demonstration, and by about 10% during demonstraction activities.

Section 5
Other Technology Requirements

Volatile components generated from the site may increase with bioremediation as a result of soil tillage. However, previous studies by the developer have indicated that these increased levels are below permissible exposure limits, and organic vapor analyzers used to monitor the breathing zone in the treatment plot never indicated the presence of airborne VOCs.

5.1 Environmental Regulation Requirements

Federal, state and local regulatory agencies may establish cleanup standards for the remediation and may require permits to be obtained prior to implementing the GRACE Bioremediation Technologies DARAMEND™ Bioremediation Technology. Most federal permits will be issued by the authorized state agency. Federal and state requirements may include obtaining a hazardous waste treatment permit or modifying an existing permit regulating these activities on a given site. A permit would be required for storage of contaminated soil in a waste pile for any length of time and for storage in drums onsite for more than 90 days. Air emission permits will probably not be required since VOCs are generally not a problem at these types of sites. Local agencies may have permitting requirements for construction activities (e.g., excavation and greenhouse), land treatment, and health and safety.

Section 2 of this report discusses the environmental regulations that apply to this technology. Table 2-l presents a summary of the federal and state ARARs for the GRACE Bioremediation Technologies DARAMEND™ Bioremediation Technology.

5.2 Personnel Issues

For site preparation and pretreatment operations (excavation, screening, mixing, amending, and homogenizing), the number of workers required is a function of the volume of soil to be remediated. During the demonstration, these tasks were contracted out and generally required 2-4 people using heavy earth-moving equipment working 12-hr days. If multiple treatment cycles are used, additional labor will be required to replace the treated soil with contaminated soil for the next treatment cycle. Since this was not done during the demonstration, the amount of labor required is estimated to be similar to that required for the pre-treatment activities. Once set up and "running," the process is not labor-intensive. Two people working a standard 40-hr week can till the plot once a week and irrigate it as necessary, take daily moisture and temperature readings, sample to determine the progress of bioremediation, maintain the facility and equipment, and keep the leachate collection system and treatment train operational.

Health and safety issues for personnel are generally the same as those for all hazardous waste treatment facilities. That is, they must have completed the OSHA-mandated 40-hr training course for hazardous waste work, have an up-to-date refresher certification, and be enrolled in a medical surveillance program to ensure that they are fit to perform their duties and to detect any symptoms of exposure to hazardous materials.

Emergency response training is the same as the general training required for operation of a treatment, storage, and disposal (TSD) facility. Training must address fire-related issues such as extinguisher operation, hoses, sprinklers, hydrants, smoke detectors, and alarm systems. Training must also address contaminant-related issues such as hazardous material spill control and decontamination equipment use. Other issues include self-contained breathing apparatus use, evacuation, emergency response planning, and coordination with outside emergency personnel (e.g., fire/ambulance).

For most sites, PPE for workers will include gloves, hard hats, steel-toed boots, goggles, and Tyvek®. Depending on contaminant types and concentrations, additional PPE may be required. Noise levels should be monitored during site preparation and pretreatment activities to ensure that workers are not exposed to noise levels above a time-weighted average of 85 decibels, over an 8-hour day. Noise levels above this limit will require workers to wear additional hearing protection.

5.3 Community Acceptance

Potential hazards to the community include exposure to particulate matter released to the air during site preparation and pretreatment activities. Air emissions can be minimized by watering down the soils prior to excavation and handling, or by conducting operations in an enclosure.

Using multiple treatment cycles may also mitigate community exposure concerns. Depending on the scale of the project, the GRACE Bioremediation Technologies DARAMEND™ Bioremediation Technology may require contaminated soils to remain in the treatment plot for extended periods of time. This is not expected to expose the community to any airborne particulate matter, because the process requires that the soil moisture content be maintained within a specific range for amendment to be effective.

Noise may be a factor to neighborhoods in the immediate vicinity of treatment. Noise levels may be elevated during site preparation and pretreatment activities since heavy earth-moving equipment will be used. Although this is a relatively short period of time in relation to the total treatment time frame, multiple treatment cycles will make this a recurring problem. During actual treatment, however, there will be no noise except for that associated with tillage.

Section 6
Technology Status

This section discusses the experience of the developer in applying the GRACE Bioremediation Technologies DARAMEND™ Bioremediation Technology. It also examines the capability of the developer in using this technology at sites with different volumes of contaminated soil.

6.1 Previous Experience

The effectiveness of a number of soil amendments for enhancing bioremediation of soils contaminated with high concentrations of CPs and PAHs (major components of creosote) was evaluated at bench- and pilot-scale.

Bench-scale research on eight different soil samples collected from wood treatment sites located throughout Canada showed that the strongest positive effect on bioremediation was obtained by addition of solid-phase, organic soil amendments prepared to a specific nutrient content and PSD. Treatment of soil with such amendments facilitated establishment of active populations of PCP-degrading bacteria in soils with PCP concentrations as high as 2170 mg/kg. Residual PCP concentrations of 0.7 to 8 mg/kg were attained. Other bench-scale work indicated that the same organic soil amendments can be used to enhance microbial decomposition of PAHs and petroleum hydrocarbons. Significant reductions in soil toxicity was also observed. Positive results in the bench-scale investigations led to both in situ and ex situ pilot-scale demonstrations of the technology.

The pilot-scale demonstration was performed at the Domtar Wood Preserving site where several decades of wood treatment had resulted in deposition of CPs at concentrations of 680 mg/kg and total PAH concentrations of more than 1400 mg/kg. The soil was a fine sandy loam (72.3% sand, 23.5% silt, and 4.2% clay) with a pH of 7.4 and an organic carbon content of 1.8%. Both *in situ* and ex situ treatment plots showed dramatic reductions in total PAHs using only the proprietary organic amendment and tillage. The *in* situ concentations were reduced from 15,670 to 3870 mg/kg (73%) after 149 days while the ex situ concentrations were reduced from 1485 to 35 mg/kg (98%) after 207 days. The ex *situ* plot also showed reductions in PCP and TPH concentrations of 99% (from 680 to 6 mg/kg for PCP and from 6325 to 34 mg/kg for TPH).

Bench-scale tests of this technology on sediments contaminated with PAHs have also been encouraging enough that ex *situ* pilot-scale testing has started and the results are pending.

6.2 Scaling Capabilities

The Domtar Wood Preserving site represents the first full-scale application of the GRACE Bioremediation Technologies DARAMEND™ Bioremediation Technology. The SITE demonstration was conducted in conjunction with the full-scale remediation to determine its cost-effectiveness and applicability to other soils and contaminants.

The DARAMEND™ technology has successfully remediated 1,500 tons of soil *ex-situ* and 3,500 tons of soil *in-situ* (2 ft. of near-surface soil) at the former Domtar Wood Preserving Facility. The remediated soil met clean-up criteria set by the Canadian Council of Ministers of the Environment, including a 5 mg/kg criterion for pentachlorophenol. In 1995, full-scale treatment of a second 1,500 ton batch of soil was initiated at the site.

In the United States during 1996, the DARAMEND™ technology was successfully applied at full-scale at a former wood perserving site in Minnesota. Late in 1996 a large-scale field treatability demonstration was initiated in association with remedial actions at the Montana Pole Superfund site in Butte, Montana. Commencement of a full-scale project is planned for the summer of 1997 in Washington State.

Key developmental work on the technology is focusing on improving kinetics and expanding applicability with respect to contaminant type. The range of contaminants effectively dealt with by the DARAMEND™ technology has now been expanded to include phthalates. Concentrations of phthalates have been rapidly reduced from thousands toeass then 100 mg/kg during bench-scale studies and pilot-scale work at a site in New Jersey in 1996. For example, total phthalates were reduced from 7,710 mg/kg to 47 mg/kg in soil, exhibiting a greater then 99% removal efficiency.

In addition, a second generation DARAMEND™ technology has been developed by GRACE Bioremediation

Appendix A

Vendor’s Claims

Technologies. The new technology rapidly reduces concentrations of organochlorine pesticides (e.g., DDT and Toxaphene™) and organic explosives (e.g., TNT, RDX and HMX) in soil. For example, p,p-DDT, an organochlorine pesticide, was reduced from 684 mg/kg to 1.9 mg/kg in soil and 2,4,6-trinitrotoluene (TNT), an organic explosive, was reduced from 7,200 mg/kg to 19 mg/kg in soil, exhibiting a greater then 99% removal efficiency in both cases. Extensive laboratory testing has been completed. Pilot-scale pesticide projects commenced in 1996 in South Carolina and Ontario, Canada and will continue in 1997. A pilot-scale project to demonstrate remediation of explosives-contaminated soil is expected to commence in 1997.

A.1 Introduction

Bioremediation has many advantages as a treatment technology for soils containing elevated concentrations of organic contaminants. Among the advantages:

- It can provide a final solution through complete destruction of the contaminants, thereby ending liability of the site owner.
- It is often the most cost-effective remedial option
- It is perceived by the public to be a natural, environmentally friendly technology, hence, generally faces fewer objections from stake holders, and therefore, can be more rapidly implemented.
- It has lower capital costs than other remedial options.
- It is well suited to situations in which the site owner prefers to spread site remediation costs over a number of years.

In contrast to these advantages traditional bioremediation has always had significant disadvantages in that:

- It has acquired a reputation for being unreliable.
- It is frequently unable to reduce concentrations of target compounds to the remediation criteria.
- It is only effective in soils with low to moderate concentrations of acutely toxic contaminants, such as PCP.

As a result of these advantages and disadvantages bioremediation has been implemented frequently, but has often been unsuccessful in attaining remediation criteria, particularly for highly toxic and refractory compounds such as CPs (CPs) and high molecular weight PAHs.

A.2 DARAMEND™ Bioremediation

In 1988, under sponsorship of the government of Canada, GRACE Bioremediation Technologies initiated research aimed at development of a reliable technology for bioremediation of wood preserving soils that contain elevated levels of CPs and PAHs. It was determined that less than one-third of the 10 soils studied could be effectively bioremediated by existing protocols based upon irrigation, tillage, and addition of nutrients. Additionally, the research revealed that the primary factor limiting biodegradation of PCP and PAHs in the hard-to-remediate soils was the number of microsites with environmental conditions supportive of vigorous microbiological activity (i.e., biologically active microsites with sufficient available water, dissolved oxygen, nutrients and surfaces for microbial adhesion). Continued research, focused on improving the number and quality of microbially active microsites, lead to development of a bioremediation technology based on incorporation of insoluble organic soil'amendments engineered to provide a large number of water-filled micropores with physical and chemical conditions conducive to microbiological growth. The organic soil amendments are manufactured from naturally occurring materials and are added to the soil at rates of 0.25 to 5% by weight. The physical/chemical properties of the organic soil amendments (e.g., particle size and shape, nutrient content, nutrient release kinetics) and the optimal application rate are highly soil-specific. The bioremediation technology is the subject of a patent application filed on behalf of Environment Canada, and GRACE Bioremediation Technologies has acquired the exclusive world-wide license for its commercial utilization. Currently, the technology is available throughout North America under the tradename DARAMEND™.

In 1991-I 992, a pilot-scale demonstration of the technology was conducted at an industrial wood-preserving site, owned by Domtar Inc, in Trenton, Ontario, Canada. The demonstration included ex situ treatment of 10 tonnes of soil in 1991, and 100 tonnes of soil in 1992. The soils contained PCP and PAHs at initial concentrations of approximately 700 mg/kg and 1,500 mg/kg, respectively. In both demonstrations, reductions of 98-99% and 9597% in the total concentrations of CPs and PAHs, respectively, were attained.

In 1993 and 1994, a full-scale demonstration of the technology was successfully completed at the same site. During the full-scale demonstration more than 4,000 tonnes of soil was remediated to below the required criteria (i.e., TCPs to less than 5 mg/kg; carcinogenic PAH compounds to less than 10 mglkg).

In 1993, DARAMEND bioremediation was applied to silty-clay sediment dredged from an industrial harbour on Lake Ontario. During the 150 tonne pilot-scale demonstration the sediment PAH concentration was reduced from more than 1,200 mg/kg to less than 100 mglkg concentration.

DARAMEND has recently been implemented using a biopile system at sites where available space is limited.

In 1995, modifications of the DARAMEND technology were implemented at industrial sites in the United States where soils are contaminated with phthalates and organochlorine pesticides (e.g., DDT, chlordane, toxaphene, dieldrin). At other sites, soils containing herbicides including 2,4-D and 2,4,5-T are being remediated.

A United States patent No. 5,411,664 covering aspects of the technology was issued in May of 1995.

The major components of the technology are:

- DARAMEND organic soil amendments that are engineered to have soil-specific properties and are applied at rates determined during bench-scale op-timization studies conducted on the soil to be remediated.
- A rapid, low-cost process monitoring procedure that utilizes bench-scale microcosms and radio-labelled analogues of the target compounds to rapidly provide data on biodegradation of the target compound(s).
- Specialized deep-tillage and soil mixing equipment,
- Knowledge and experience provided by GRACE Bioremediation Technologies' bioremediation personnel.

In contrast to traditional bioremediation the DARAMEND technology provides the following advantages:

- Increased reliability, which is achieved by engineering the DARAMEND organic soil amendments and designing other treatment conditions on a soil specific basis.
- Reduced analytical costs since standard analytical techniques utilized in process monitoring are replaced with radioisotope microcosm studies conducted in parallel with each field bioremediation project.
- Lower operation and maintenance costs, because application of soil amendment is only performed once at the initiation of treatment, tillage is performed less frequently, and remediation criteria are attained more rapidly.
- Ability to bioremediate soils with higher initial concentrations of toxic contaminants and more consistently attain low residual concentrations of refractory contaminants such as carcinogenic PAHs and PCP
- Reduction or elimination of soil toxicity.
- Greater treatment depth in landfarming operations (i.e., a full two feet), due to utilization of specialized tillage equipment.
- Capacity to effectively bioremediate soils with high clay content, due to the ability of the soil amendments and tillage equipment to favourably alter soil structure.
- Ability to bioremediate sediments without dewatering, due to the highly adsorptive nature of the DARAMEND soil amendments.
- Reduced evolution of VOCs and odours due to the adsorptive properties of the organic amendments.

A.3 Summary

DARAMEND is an innovative, cost-effective bioremediation technology. Its effectiveness has been proven at pilot-scale and full-scale at several sites in North America. The advantages of DARAMEND technology are most apparent, and valuable, when the soil or sediment to be remediated:

- contains highly refractory contaminants such as carcinogenic PAHs;
- contains high concentrations of acutely toxic contaminants such as PCP;
- has high clay content, or
- is subject to stringent remediation criteria.

GRACE Bioremediation Technologies' DARAMEND bioremediation technology is now available to site owners, consulting and engineering companies throughout North America and Europe.

DARAMEND™ Bioremediation of Soils Containing Chlorophenols and Polynuclear Aromatic Hydrocarbons (Full-Scale Demonstration)

Final Report

Prepared by

GRACE Bioremediation Technologies
formerly
Environmental Engineering Group
Grace Dearborn, Inc.

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Executive Summary

Daramend™ Bioremediation of Soils Containing Chlorophenols and Polynuclear Aromatic Hydrocabons (Full-Scale Demonstration)

Remediation of soils containing chlorophenols and creosote at wood preserving sites is of particular importance in Canada due to the large number of such sites. Bioremediation can be advantageous to landowners since it is based upon microbial biodegradation of the target compounds and can therefore eliminate future liability. In addition, it is one of the most cost-effective remedial options.

Daramend™ bioremediation was developed under the sponsorship of, and is owned by, the Government of Canada. GRACE Dearborn Inc. has acquired the licence for worldwide application of this technology that has been successfully applied at bench- and pilot-scale to remediate soils containing chlorophenols (CPs) and polynuclear aromatic hydrocarbons (PAHs). Daramend bioremediation technology involves the application of solid-phase, biodegradable, organic soil amendments of specific particle-size distribution, nutrient content and nutrient-release kinetics to soils at rates determined by bench-scale optimization experiments. The specific application rates and composition of Daramend products are considered to be proprietary information. The application rates typically range from 0.5 to 5% (w/w).

This report describes a demonstration of full-scale, *in situ* and ex *situ,* Daramend bioremediation at the former Domtar Inc. Wood Preserving site in Trenton, Ontario.

During the *in situ* demonstration, approximately 3,500 tonnes of soil in a 4,800 m^2 area were treated. The 4,800 m^2 area was divided into 49 separate sampling areas of approximately 100 m^2 each. In these sampling areas, initial total CP concentrations ranged from 0.92 mg/kg to 27.8 mg/kg and total PAH concentractions ranged from 8.7 mg/kg to 662 mg/kg. The results indicated that, during 305 days of treatment, which included a period of 136 days when the soil was frozen or soil temperatures were not conducive to microbial activity (<5°C), CP concentrations in all 49 sampling areas were reduced to below the Canadian Council of Ministers of the Environment (CCME, 1991) remediation criteria for industrial soils (5 mglkg for each listed CP). During the same time period the concentrations of all nine CCME listed PAHs were reduced to below the CCME remediation criteria for industrial soils in all but 3 of the 49 sampling areas. In these 3 sampling areas, concentrations of two of the more recalcitrant higher molecular weight PAHs, benzo(b)fluoranthene and benzo(a)pyrene remained above the CCME remediation criteria (10 mg/kg) at concentractions ranging from 12 to 17 mglkg.

During the ex situ demonstration, approximately 1,500 tonnes of soil were treated using Daramend bioremediation in two fully contained treatment cells, designated Treatment Cell 1 and Treatment Cell 2.

In Treatment Cell 1, the mean total CP concentration was reduced by 91% (from 157 to 14 mglkg) after 282 days of Daramend treatment. The CCME criteria for industrial soils was reached for all listed CPs except pentachlorophenol (PCP). The mean concentration of PCP, the predominant species, remained above the CCME criteria (5 mg/kg) at 12.7 mg/kg. The mean total PAH concentration in Treatment Cell 1 was reduced by 67% (from 439 to 44 mg/kg) after 282 days of treatment. The CCME criteria for industrial soils were reached for 7 of the 9 listed PAHs. Concentrations of two of the more recalcitrant higher molecular weight PAHs, benzo(b)fluoranthene (16.3 mg/kg) and benzo(a)pyrene (10.6 mg/kg) remained above the CCME remediation criteria for industrial soil (10 mg/kg).

In Treatment Cell 2, the mean total CP concentration was reduced by 98% (from 102 to 2 mg/kg) after 175 days of Daramend treatment. The CCME criteria for industrial soils were reached for all listed CPs (5 mg/kg for each listed CP). The mean total PAH concentration in Treatment Cell 2 was reduced by 87% (from 619 to 79 mg/kg) after 251 days of Daramend treatment. The CCME criteria for industrial soils were reached for all listed PAHs.

The number of treatment days cited for Treatment Cells 1 and 2 include a period of 55 days when the soil was frozen or soil temperatures were not conducive to microbial activity (<5°C).

Microbiological monitoring indicated that Daramend bioremediation did not increase the number or alter the identity of bacteria being transported offsite by air, surface run-off water or soil transport vectors. Laboratory microcosms containing soil collected from ex situ Treatment Cell 1 supported extensive mineralization of added ^{14}C-PCP, thereby verifying that the observed reductions in PCP concentration were due to biodegradation.

Scale-up of the technology from pilot- to full-scale requried a number of modifications in procedures and equipment. For the *in situ* portion of the demonstration, the main technical issue was development of a protocol for efficiently removing large subsurface debris that hindered incorporation of soil amendments and subsequent soil tillage. For the ex *situ* portion of the demonstration, the main technical issue was modification of irrigation protocols to allow efficient irrigation of soil during treatment. Details on these and other technical issues and their resolution along with the estimated cost of applying the technology at commercial scale are presented in this report.

In situ/On-Site Bioremediation of Soils Containing Chlorinated Phenols and Polynuclear Aromatic Hydrocarbons

Final Report

Prepared by

GRACE Bioremediation Technologies
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GRACE Dearborn, Inc.

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Executive Summary

In situ/On-Site Bioremediation of Soils Containing Chlorinated Phenols and Polynuclear Aromatic Hydrocarbons

Remediation of soils impacted with toxic organic compounds is an issue of increasing concern to society throughout North America and the world. Remediation of soils containing CPs and creosote at wood preserving sites is of particular importance in Canada due to the large number of such sites.

Processes that can be used for remediation of soils contaminated with organic wood preservatives include soil washing, incineration, landfilling, and bioremediation. Bioremediation, can be advantageous to landowners since it is based upon microbial biodegradation of the target compounds and can therefore eliminate future liability. In addition, it is one of the most cost-effective remedial options.

Variables that can affect the biodegradation of organic pollutants, and hence the effectiveness of bioremediation, include the structure, reactivity and concentration(s) of the target compounds, their interaction with other compounds present in the soil, and the physical, chemical, and biological characteristics of the soil.

Daramend™ bioremediation was developed under the sponsorship of, and is owned by, the Government of Canada. GRACE Dearborn Inc. has acquired the licence for worldwide application of this technology that has been successfully used at bench-scale to remediate soils containing CPs and pPAHs. Daramend™ bioremediation involves the addition of solid-phase, particulate organic soil amendments to soils at rates determined by bench-scale optimization experiments. The PSD, nutrient content and nutrient-release kinetics of Daramend soil amendments are specific to the soil being treated. The application rates and composition of Daramend products are considered to be proprietary information until patent protection is granted.

This report describes a pilot-scale demonstration of Daramend bioremediation at the Domtar Inc. wood preserving site in Trenton, Ontario.

Over the course of two years (1991-l 992), soil was treated under a variety of conditions with Daramend™. Two in situ demonstrations, and two ex situ (on-site) demonstrations were conducted. During the 1991 ex situdemonstration, the mean total chlorophenol concentration in a treatment area containing 10 tonnes of soil, was reduced from 702 mg/kg to less than the criterion established by the Canadian Council of Ministers of the Environment (CCME) for industrial soil (5 mg/kg) in 345 days. In the same demonstration, the mean total PAH concentration was reduced from 1442 mg/kg to 35 mg/kg, and the concentrations of all PAH isomers were reduced to less than the CCME criteria for industrial soil.

Similar reductions in CP and PAH concentrations were obtained during the *1992 ex situ* demonstration, in which 100 tonnes of soil were treated.

The first (1991) in situ demonstration was conducted to enable comparison between treatment with a variety of Daramend products, and controls. Reductions in chlorinated phenol concentrations were observed in all treatments; however, of those that produced statistically significant reductions, only Daramend bioremediation reduced total chlorinated phenol concentrations to below the CCME remediation criterion for industrial soils (5 mg/kg).

A second *in situ* demonstration, conducted in 1992, focused on bioremediation of soil with very high PAH concentrations (ca. 20,000 mg/kg). Soil undergoing Daramend treatment supported greater biodegradation of PAHs than the tilled control (79% vs. 48%). Due to high initial concentrations, and the short duration of the demonstration the PAH concentrations remained above the CCME criteria.

Radioisotope (^{14}C) microcosm studies were performed in the laboratory using soil collected from the treatment areas. The studies indicated that ^{14}C-labelled compounds added to the soils (anthracene, pentachlorophenol) were extensively biodegraded as evidenced by substantial evolution of $^{14}CO_2$, which is the main end product of microbial metabolism.

Standard toxicological tests, including earthworm mortality and seed germination, were performed on soil taken from the treated area and the control area after completion of the 1991 ex situ demonstration. The tests indicated that Daramend treatment had reduced or eliminated the soil's toxicity. Earthworms exposed to soil from the control area died in four days (100% mortality), while all earthworms exposed to the Daramend-bioremediated soil survived for the full 28 days of the assay (0% mortality). Similar reductions in toxicity of the treated soil were revealed by seed germination assays. For example oat seeds added to the untreated control soil failed to germinate (0% germination) while in the Daramend-bioremediated soil 93% of the oat seeds germinated. In an agricultural soil with no history of contamination, oats germinated at the same rate (93%) as in the bioremediated soil.

A full-scale demonstration of Daramend bioremediation was initiated, at the same site, in 1993. The ex situ portion of the demonstration is being audited by the EPA's SITE Program.

GRACE Bioremediation Technologies is in the process of commercializing Daramend bioremediation. Commercialization is proceeding successfully, with the creation of four full-time and four part-time positions. We have responded to commercial tenders for work on five sites in Canada, and two in the U.S. We are presently conducting commercial pilot-scale bioremediation at three sites in Canada.

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